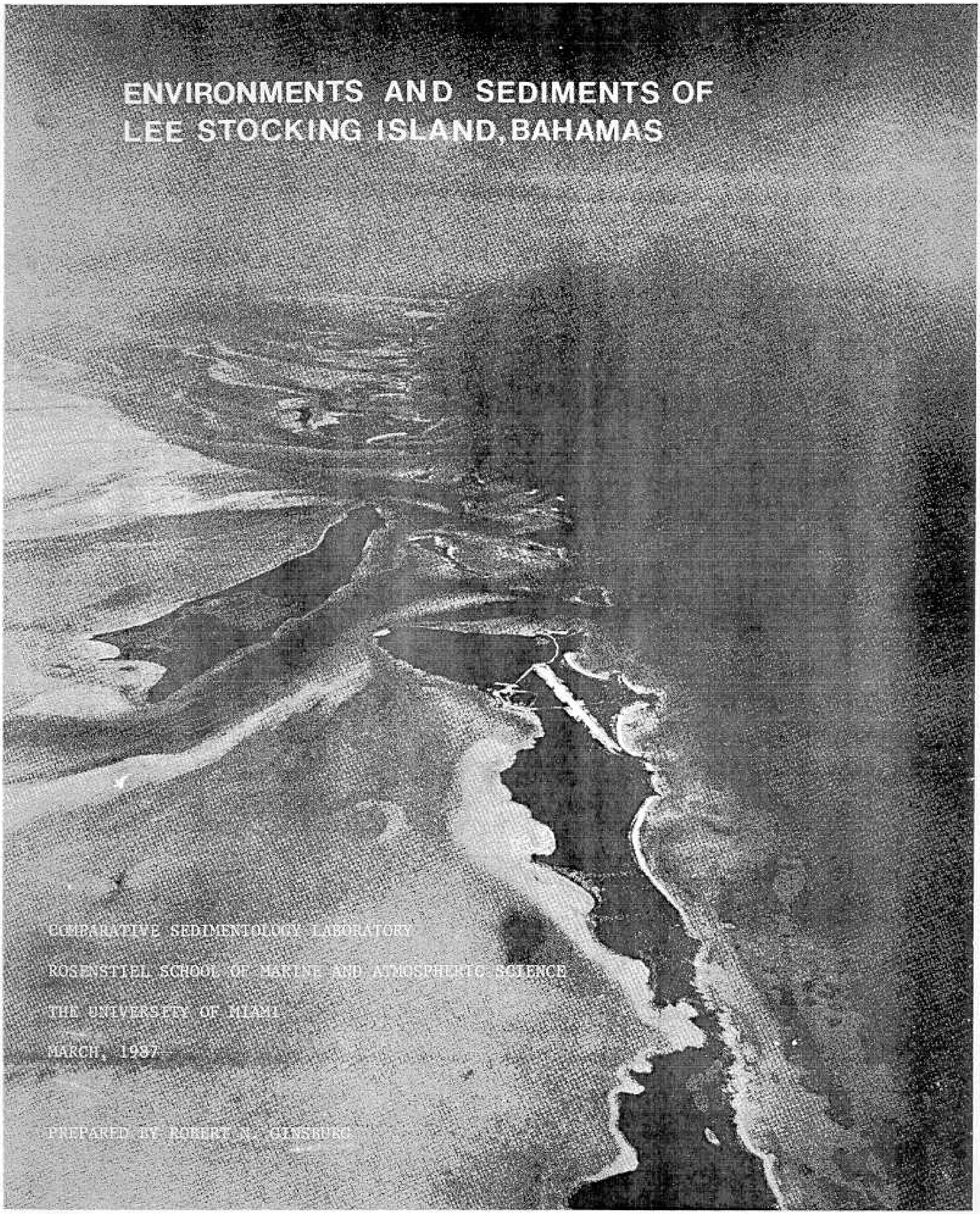
ENVIRONMENTS AND SEDIMENTS OF LEE STOCKING ISLAND, BAHAMAS



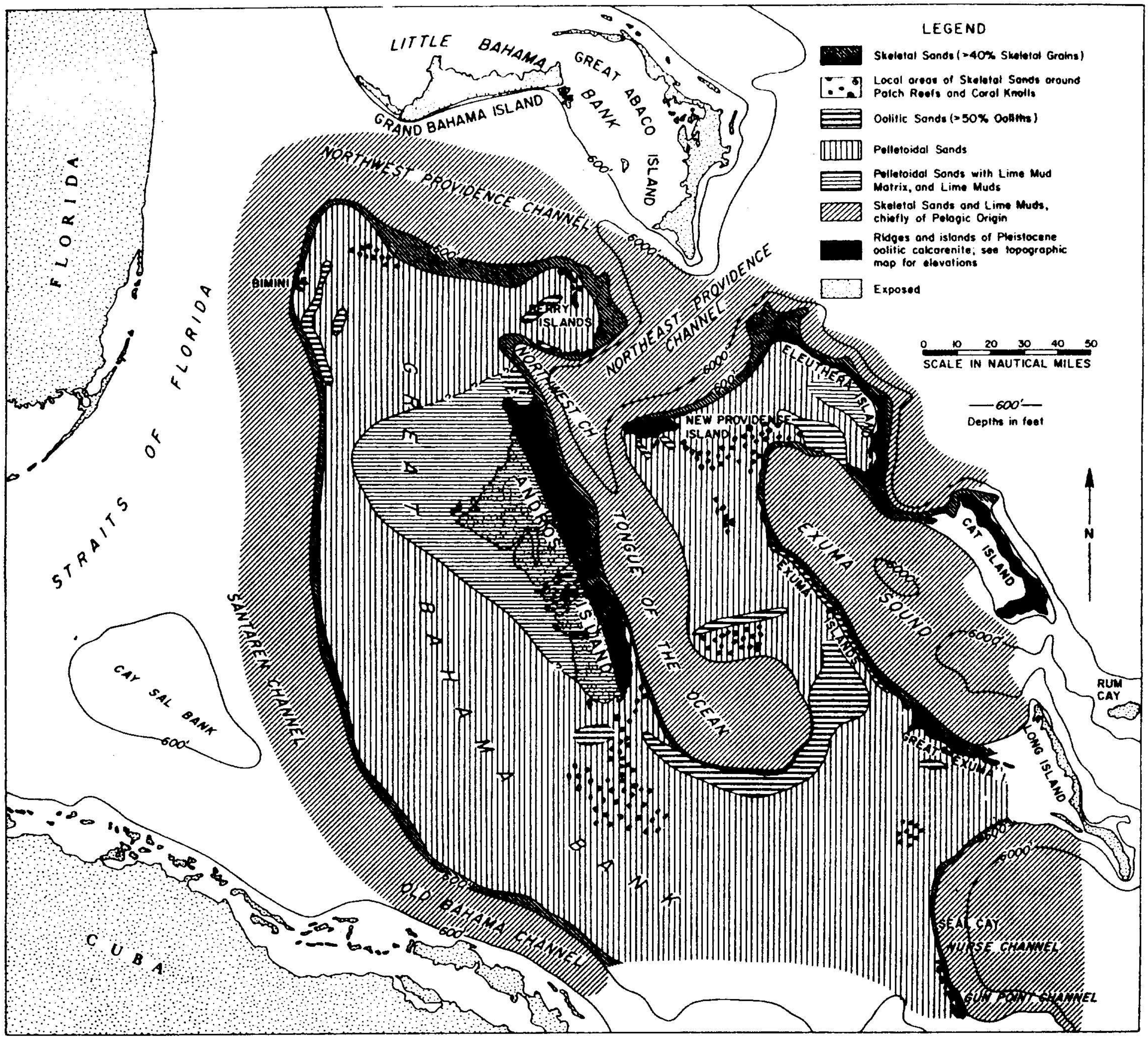
COMPARATIVE SEDIMENTOLOGY LABORATORY

ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE

THE UNIVERSITY OF MIAMI

MARCH, 1987

PREPARED BY ROBERT N. GINSBURG



Surface sediments of the Great Bahama Bank and surrounding deep sea floor. Note contours in feet and scale in nautical miles. From Traverse and Ginsburg, 1966.

INTRODUCTION TO ENVIRONMENTS AND SEDIMENTS
LEE STOCKING ISLAND, BAHAMAS

GIANT STROMATOLITES IN THE TIDAL CHANNEL, LEE STOCKING ISLAND, DEPTH 7 METERS. COURTESY OF EUGENE SHINN.

PREPARED FOR
THE INDUSTRIAL ASSOCIATES
OF THE
COMPARATIVE SEDIMENTOLOGY LABORATORY
ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE
UNIVERSITY OF MIAMI
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ANNUAL REVIEW FIELD TRIP 1987
LIST OF PARTICIPANTS

COMPARATIVE SEDIMENTOLOGY LABORATORY
FISHER ISLAND

MARCH 19 - 22, 1987

John Acuff
Denver Exploration Division
Texaco Inc.
P.O. Box 2100
Denver, CO 80201

Jack Babcock
Amoco Production Co.
P.O. Box 3385
Tulsa, OK 74102

Alton Brown
Arco Exploration & Technology
2300 W. Plano Parkway
Plano, TX 75075

Al Crawford
UNOCAL
P.O. Box 76
Brea, CA 92621

Paul Crevello
Marathon Oil Co.
P.O. Box 269
Littleton, CO 80160

John Douglas
Texaco Canada Resources

Tom Elliot
UNOCAL
P.O. Box 76
Brea, CA 92621

Ray Garber
Chevron Oil Field Research Co.
P.O. Box 446
La Habra, CA 90631

Paul Mitch Harris
Chevron Oil Field Research Co.
P.O. Box 446
La Habra, CA 90631

Susan Longacre
Texaco Inc.
Texaco Houston Research Center
P.O. Box 770070
Houston, TX 77215-0070

Robert Loucks
Arco Exploration & Technology
2300 W. Plano Parkway
Plano, TX 75075

Manfried Lutz
Shell Research B.V. (KSEPL)
Postbus 60, 2280 AB
Rijswijk (ZH)
The Netherlands

Richard H. Spaw
Marathon Oil Co.
P.O. Box 3128
Houston, TX 77253

Steve Switzer
Chevron Canada Resources Ltd.
500 - 5th Avenue S.W.
Calgary, Alberta T2P 0L7 Canada

Christian Viau
Shell Canada Ltd.
P.O. Box 2506
Calgary, Alberta, Canada T2P 3S6

Paul Wagner
Amoco Production Co.
P.O. Box 3385
Tulsa, OK 74102

Robert Ginsburg
Peter Swart
Gregor Eberli
Don McNeill
University of Miami
Fisher Island
Miami Beach, FL 33139

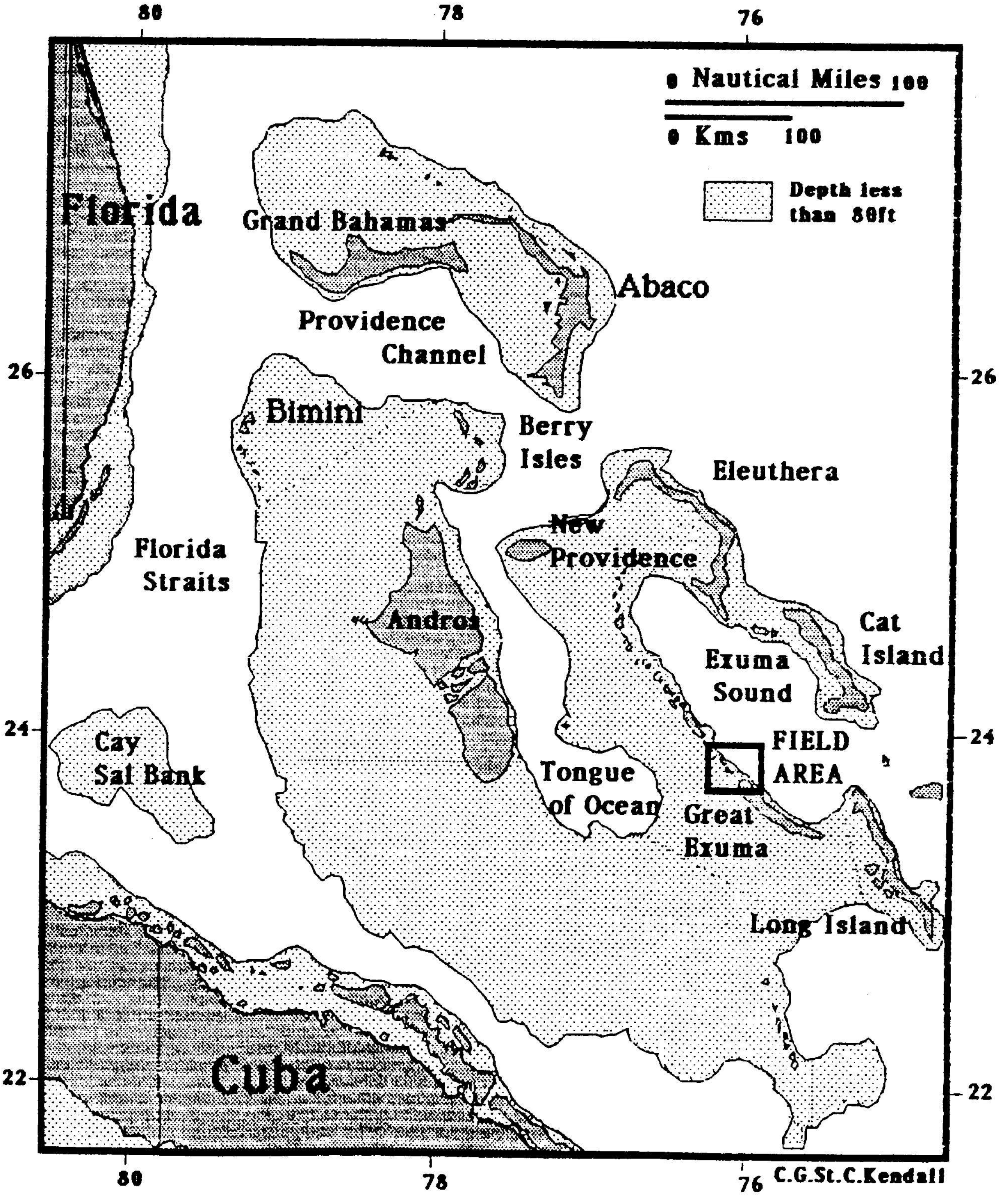


Figure 1 Bathymetry of the Bahamas Bank

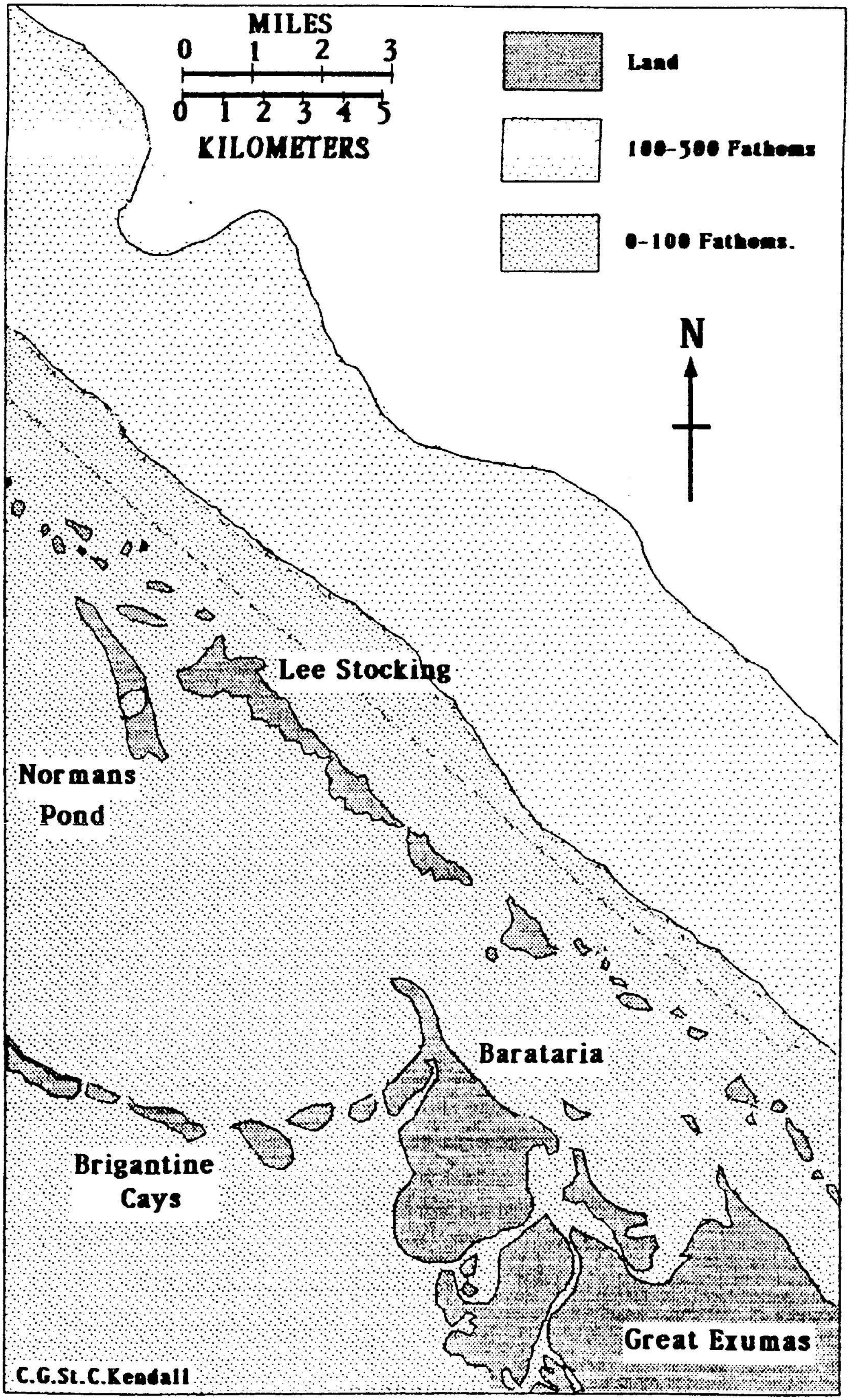


Figure 2 **General Location of Lee Stocking.**

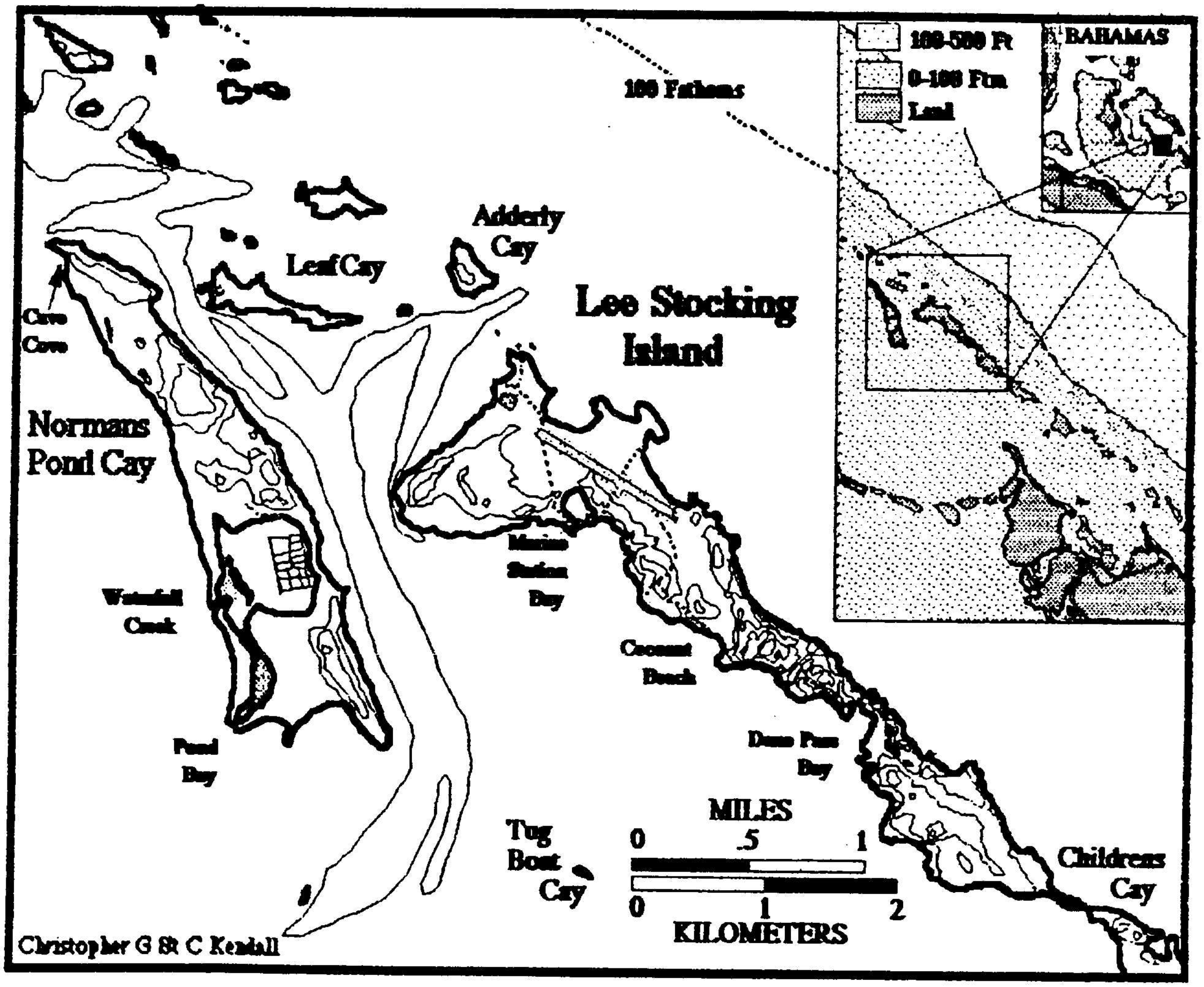


Figure 3 Location of Lee Stocking Island, the Exumas Cays, The Bahamas

Figure 4 Marine Station Bay.

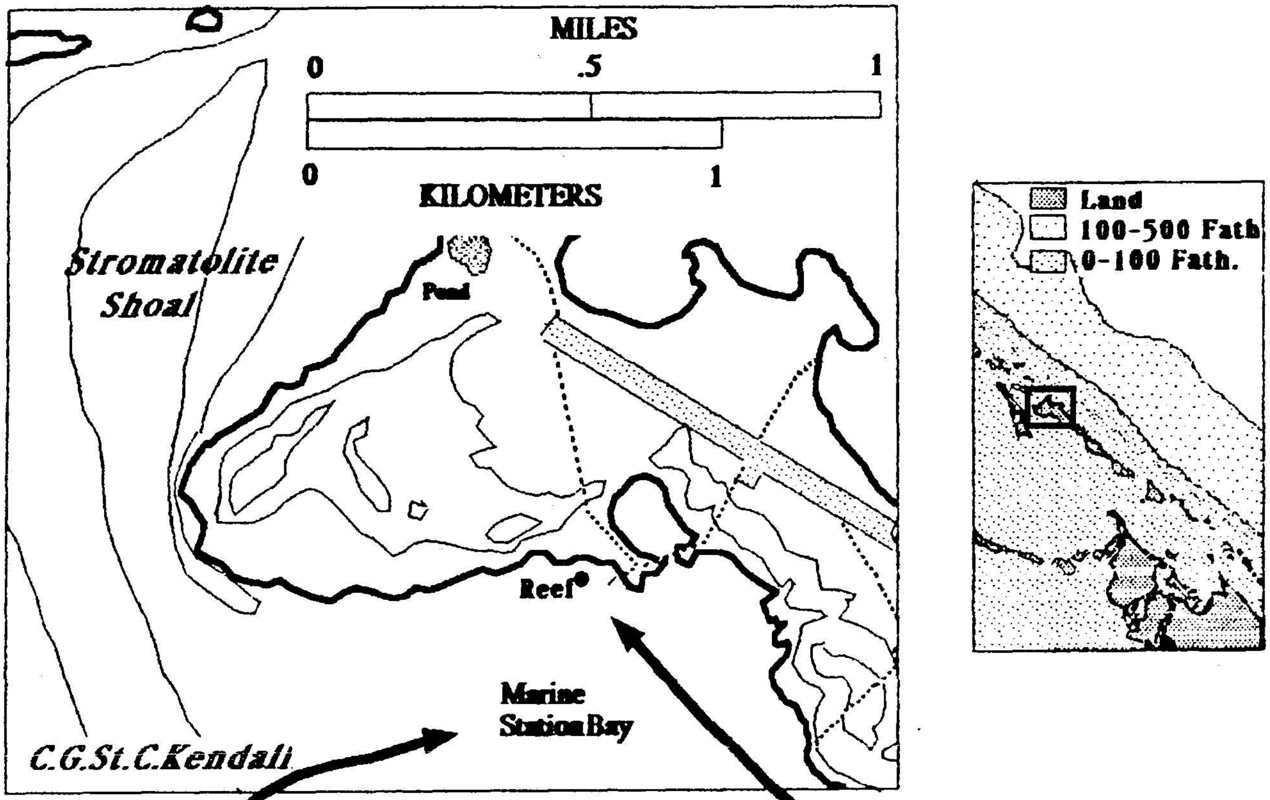


FIGURE 15

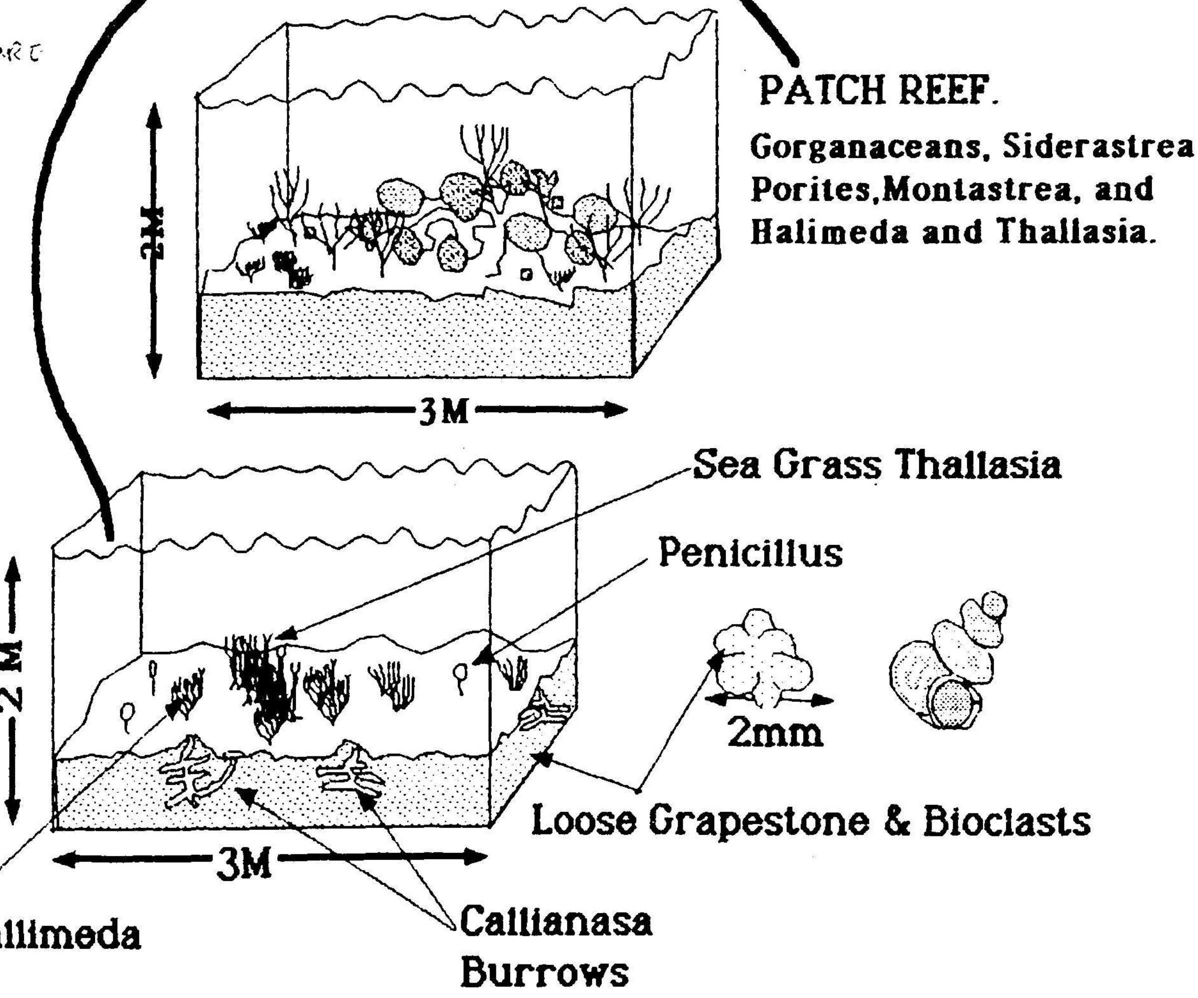
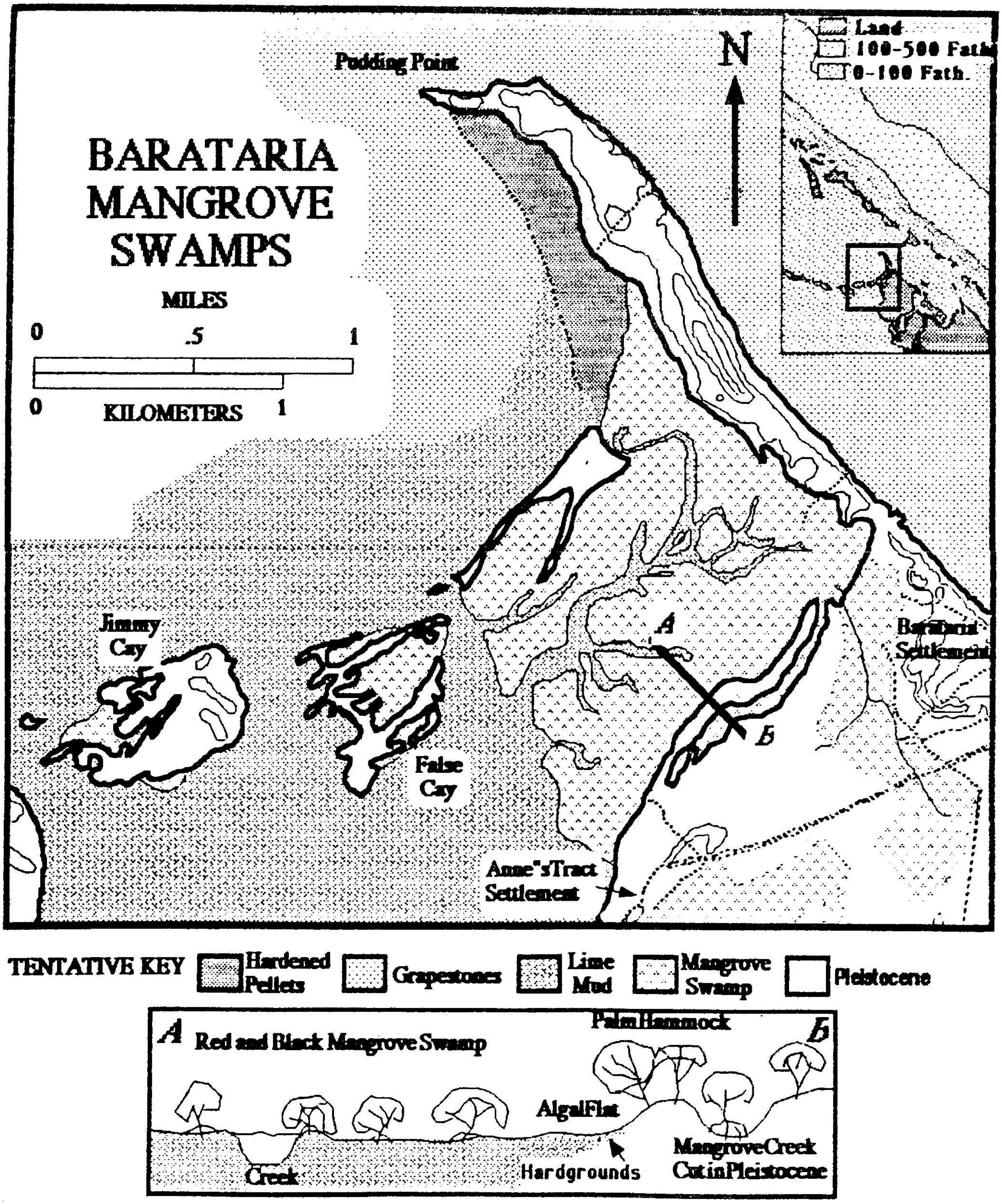


Figure 5



C.G.St.C.Kendall

Gerhardt, Daniel Joseph (M.S., Marine Geology and Geophysics)

THE ANATOMY AND HISTORY OF A PLEISTOCENE STRAND PLAIN DEPOSIT, GRAND BAHAMA ISLAND, BAHAMAS. (December, 1983)

Abstract of a master's thesis at the University of Miami.
Thesis supervised by Professor R.N. Ginsburg

The carbonate banks of the Bahamas are partially rimmed by islands of Late Pleistocene limestone. Most islands are composed of grainstone that formed as beach and eolian ridges surrounded by shallow sublittoral deposits. Although they form only a small portion of the banks, islands have a profound effect upon the surrounding area by altering the hydrographic conditions and producing a change in the sediment deposition.

Within the Bahama Archipelago, islands can be divided into two general types; 1) high narrow islands, and 2) low broad islands. Grand Bahama Island, one of the low broad types, was studied to determine the morphology and structure of the island deposits. The early cementation and numerous outcrops on Grand Bahama Island provide a special opportunity to investigate the beach-dune deposits that compose the highlands of many Bahamian islands. A 100 square-kilometer study area, located between Freeport and the Grand Lucayan Waterway, was chosen to investigate the Late Pleistocene deposits because of the high percentage of ridges and variability of ridge morphology within the area. The beach and eolian deposits were divided on the basis of structure and composition. Sea level position and the sequence of deposition for the ridges have been determined.

Approximately 95 percent of Grand Bahama is low plains that are dissected by inactive channels. Ridges, located on the southern side of the island, form less than 5 percent of the area. The ridges are shoreline deposits of beach-dune origin while the lowlands are sublittoral deposits now exposed by the lower relative position of sea level.

The limestones of the lowlands are composed of peloids, ooids, skeletal fragments, and minor amounts of mud. They are characterized by a mottled appearance resulting from the selective cementation of trace fossils produced by burrowing organisms and by the weathering of the softer matrix.

The ridges are bedded and composed of peloids and ooids. Within the study area, three ridge morphologies were delineated; 1) narrow, 1 to 10 meter high, single ridges that form a segmented line of northernmost ridges, 2) a wide, 10 to 20 meter high single ridge that extends for over 6 kilometers, and 3) a series of low closely spaced ridges that forms a strand plain 2 to 3 kilometers wide and 7 kilometers long.

A principal focus of this study was the subdivision of the ridges into two parts, beach and eolian. The beach deposits, located in the lower 1 to 2 meters of the ridges, are characterized by centimeter thick beds that are 1 to 5 meters long and are composed of peloids, ooids, and skeletal material. Low angle truncations and wedge sets are common and the beds dip predominately seaward. Keystone vugs (small 1 to 5 millimeter voids) are a common feature in the upper beach deposits and are considered indicative of swash zone deposition.

The eolian deposits, located in the upper part of the ridges, are composed of 3 parts; 1) a symmetrical mound, 1 to 2 meters high and 20 to 30 meters wide that has continuous laminations, 2) a group of seaward dipping laminations that overlies the mound and is usually less than 2 meters thick, and 3) a wedge of foresets that dip at 28 to 32 degrees landward and generally composes less than 25 percent of the eolian deposits. All of the ridges were deposited from the south and were non-migrating.

The history of the island was interpreted by internal characteristics, morphology, and the spatial relationships of the ridges. The position of sea level was determined for the strand plain ridges using keystone vugs as a sea level indicator. The northern ridges were deposited at a highstand of 7 to 8 meters above present, while the southern ridges were deposited as the sea level fell. The multiple ridges probably formed as offshore bars that built up above sea level, stranding the previous beach. Sediment was supplied to the beach from the stabilized sand flats bankward of the ridges and was transported to the beach through tidal channels that dissected the flats.

Strand plains, like the one described here are probably characteristic of the low, broad islands. In the fossil record they would appear as sheets of bedded grainstones overlying shallow marine deposits. Once recognized, such fossil islands might be expected to have reefs or lime sands on their seaward sides and lime muds or wackestones on the lee sides.

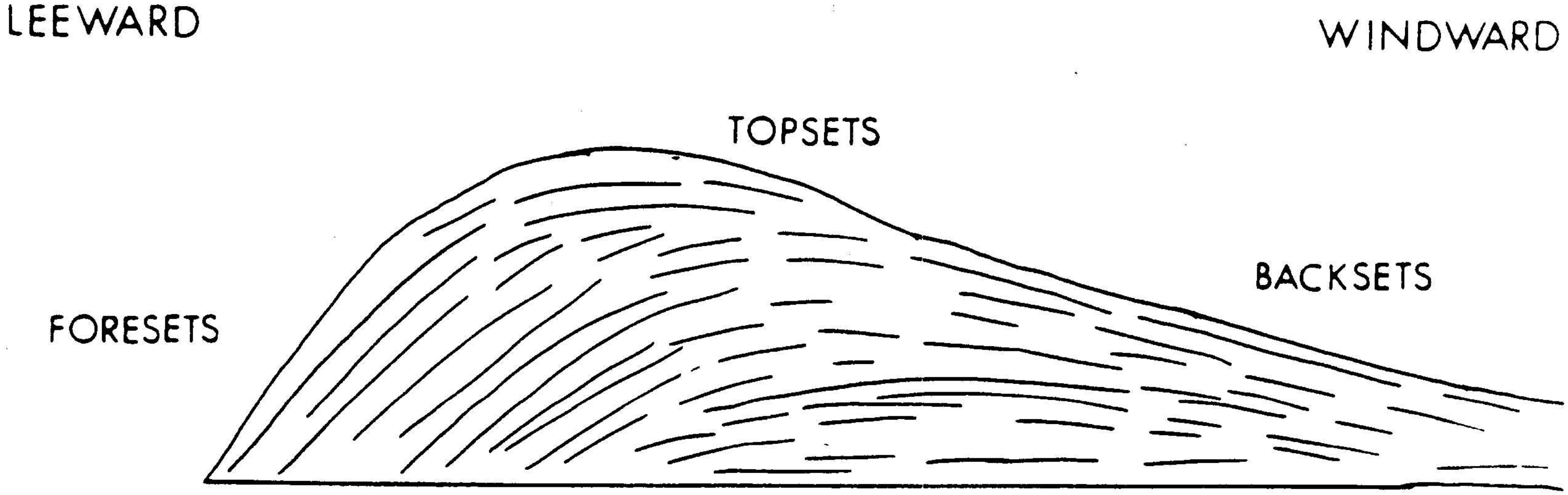
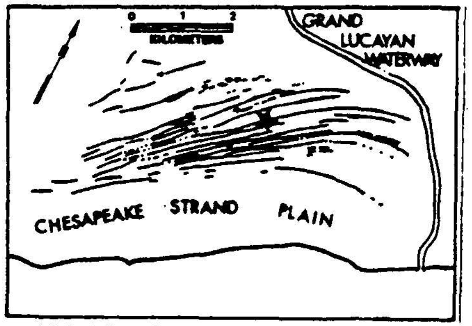
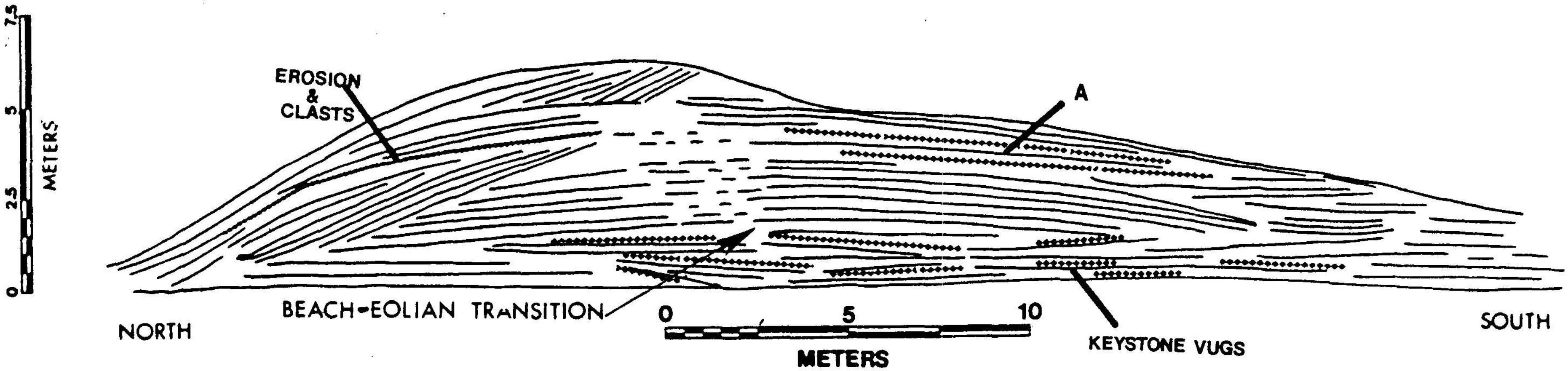


Figure 16:IDEALIZED EOLIANITE STRUCTURE

This idealized diagram of eolianite structure shows the bedding of a simple dune. Seaward is to the right. The dunes of Grand Bahama Island are typically composed of only 10 to 30 percent high angle foresets. The lower beds form a low symetrical mound 1 meter high and are often transitional with the underlying beach deposits.



LOCATION OF OUTCROP



STRUCTURE OF CATHY ROAD EOLIANITE - WEST SIDE

FIGURE 17: The Cathy Road outcrop is a ridge, 8 meters high, that is predominatly eolian with 1 to 2 meters of beach deposits at the base. In the lower meter, keystone vugs, wedge sets, short length beds, and low angle truncations all indicate beach deposition. Immediatly overlying the beach beds, the character of the rock subtly changes. The length of the individual beds increases, often to the length of the ridge. The beds are usually laminations as opposed to the centimeter thick beds in the beach deposits. Numerous truncations and wedge sets are absent above the lower two meters. The occurrence of two long thin beds of keystone vugs on the seaward side of the ridge are interpreted as storm or high water deposits. No other features suggest normal beach deposition at this height.

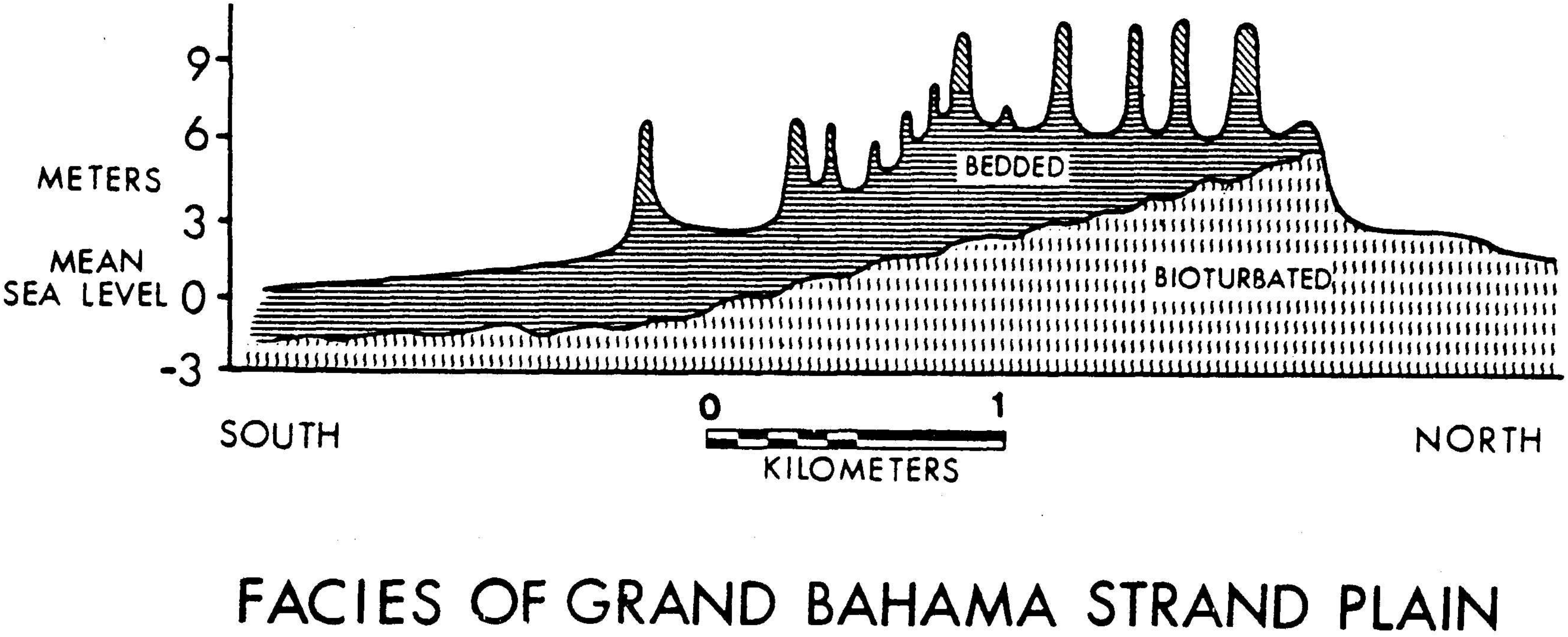
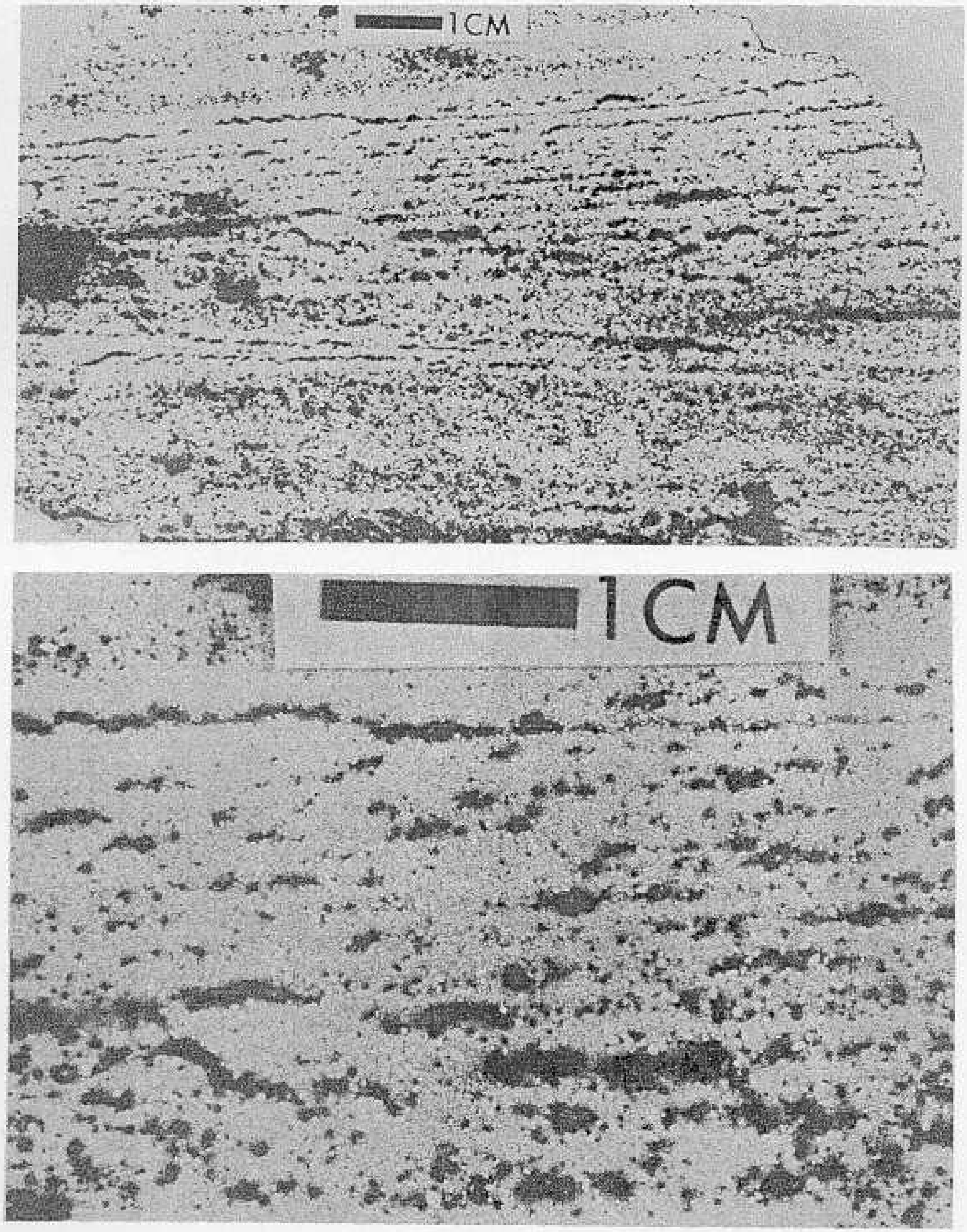
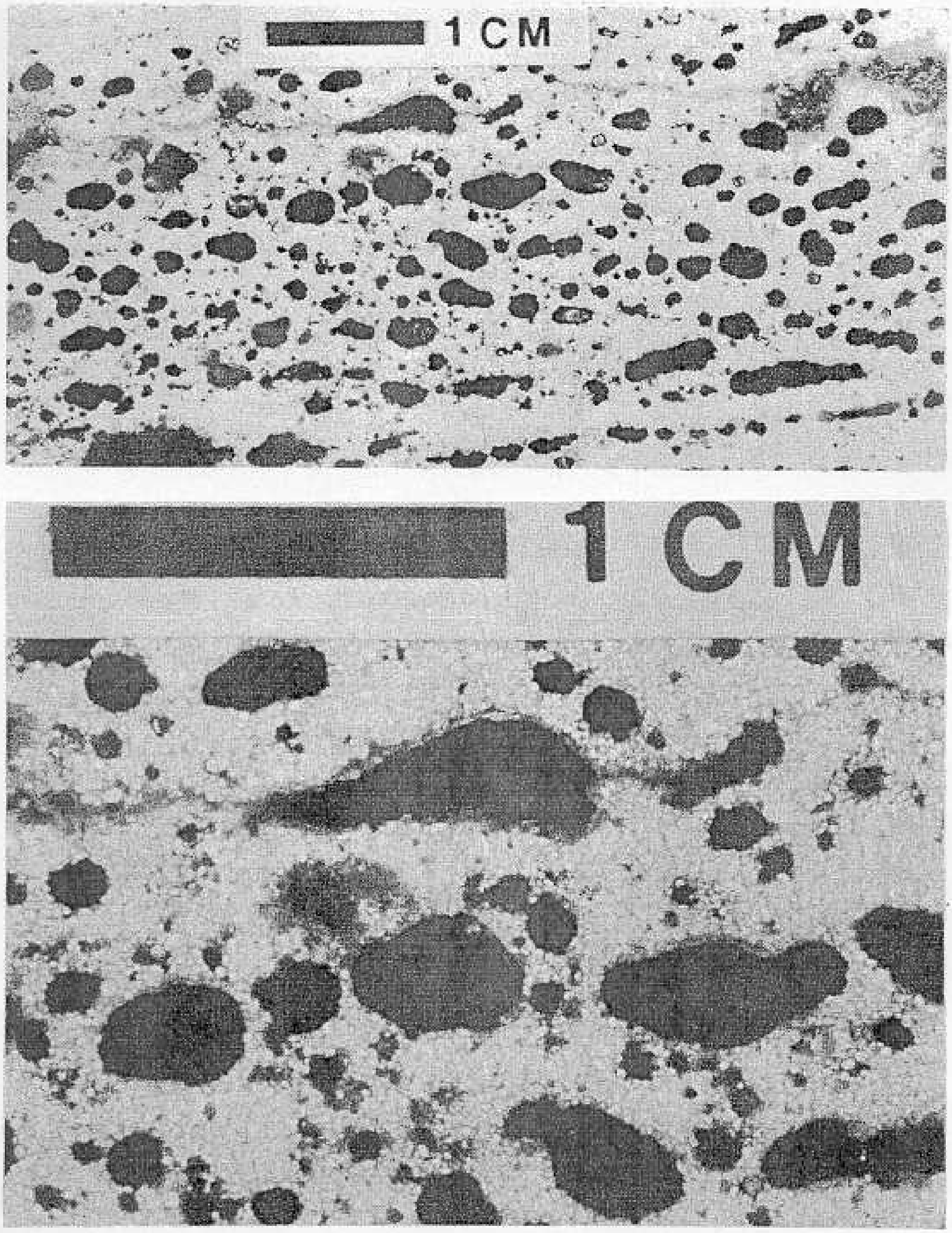


Figure 25: FACIES CROSS-SECTION OF THE CHESAPEAKE STRAND PLAIN
The bedded beach and eolian facies forms a seaward dipping unit that overlies the bioturbated marine facies. In the northern edge of the strand plain, the bioturbated unit attains its highest elevation of 5 meters.



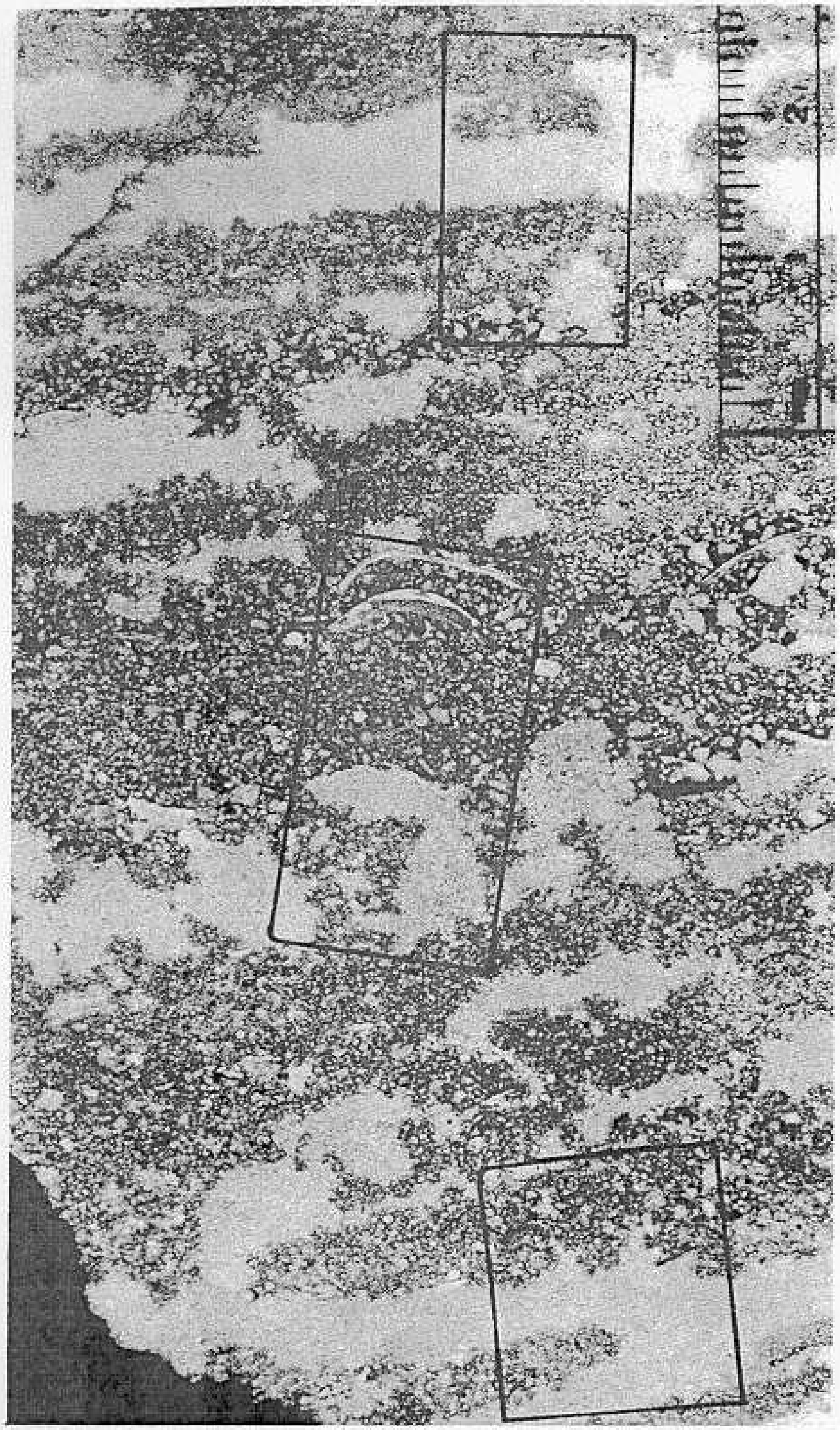
LINEAR KEYSTONE VUGS

The upper photograph shows the elongate linear type of keystone vug within a wedge shaped set of beds. The vugs highlight the bedding planes. The lower photograph is a close up of the linear vugs; note the linear shape and relatively low profile of the vugs. The sample is from the lower meter of the Cathy Road outcrop (figure 17).



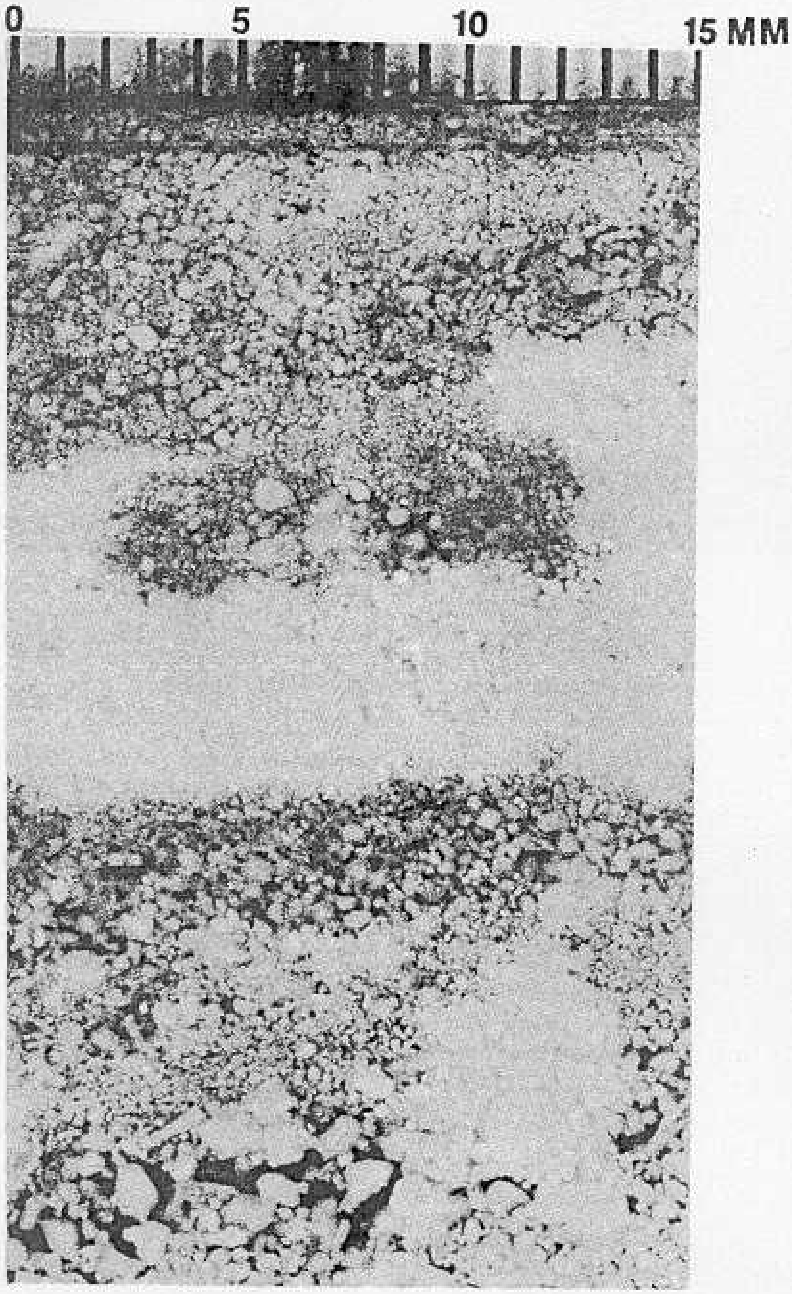
SUBCIRCULAR KEYSTONE VUGS

Photographs showing examples of the large sub-circular keystone vugs. The rock sample has been impregnated with colored polyester resin to highlight the vugs. Note the flat base and arched roof of the vugs and the grain size vs vug size. Sample is from the lower meter of the Cathy Road outcrop (figure 17).



DIFFERENTIAL CEMENTATION OF LAYERS

The sample from a beach deposit was impregnated with colored resin to highlight areas with little cement. The layers with smaller grain size have a greater percentage of cement. The outlined boxes are shown in the following figures.



DIFFERENTIAL CEMENTATION -A-

Enlarged section -A- from figure 58 indicated that the finer grains (in light areas) have a higher percentage of cement when compared to the coarse grained layers.

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Giant subtidal stromatolites forming in normal salinity waters

Robert F. Dill*, Eugene A. Shinn†, Anthony T. Jones‡, Kevin Kelly‡ & Randolph P. Steinen§

* 610 Tarento Drive, San Diego, California 92106, USA
† Department of the Interior, Geological Survey, Fisher Island Station, Miami Beach, Florida 33139, USA
‡ University of Hawaii, Honolulu, Hawaii 96822
§ University of Connecticut, Storrs Connecticut 06268, USA

We report here the discovery of giant lithified subtidal columnar stromatolites (>2 m high) growing in 7–8 m of clear oceanic water in current-swept channels between the Exuma Islands on the eastern Bahama Bank. They grow by trapping ooid and pelletal carbonate sand and synsedimentary precipitation of carbonate cement within a field of giant megaripples. The discovery is important to geologists and biologists because similar organo-sedimentary structures built by a combination of cementation and the trapping of sediment by microbes were the dominant fossil types during the Precambrian. Stromatolites are thought to have been responsible for the production of free oxygen and thus the evolution of animal life[1,2]. Until the discovery of small lithified subtidal columnar stromatolites in the Bahamas[3], the only subtidal marine examples known to be living while undergoing lithification were in the hypersaline waters of Hamelin Pool at Shark Bay, Western Australia[4–7]. Shark Bay stromatolites range from intertidal to the shallow subtidal with the larger columns reaching 1 m in height. The Shark Bay stromatolites have strongly influenced geological interpretation; by analogy, many ancient stromatolites have been considered to have grown in intertidal and/or hypersaline conditions[8], although hypersalinity was not a necessity for growth during the Precambrian because grazing metazoan life had not then evolved.

Stromatolites from the Exuma Islands occur in one of the many channels that exchange normal oceanic water from the deep Exuma Sound through the Pleistocene eolianite islands to the shallows of the eastern Bahama Bank. Those described here are from the channel separating Lee Stocking Island from Adderley and Normans Pond Cays (Fig. 1). The Exuma Islands are well known to carbonate geologists for their spectacular eolian carbonate dunes and ooid tidal deltas[9,10]. Exuma Sound has precipitous margins and a maximum depth of ~1.5 km. The eastern portion of Exuma Sound is open to the Atlantic Ocean and its waters which flood the stromatolites at high tide are exceptionally clear and of normal oceanic salinity (37–38‰). Underwater visibility in the tidal channel during flood tide is often >20 m. Ebb tidal waters from the shallow banks are more saline (as much as 40‰) due to evaporation, and have a visibility of 5–10 m, depending on weather conditions. Tides are diurnal and create currents between islands ranging between 60 and 100 cm s^{-1}.

To date, we have found growing stromatolites only associated with migrating 1- to 2.5-m-high ooid sand dunes. The stromatolites occur as individuals or as large, coalesced bioherms that form rows perpendicular to tidal flow (Fig. 2) and as randomly-spaced individuals of variable height. Randomly-spaced individuals are usually grouped in irregular-shaped patches 5–10 m across. The tops of the larger fence-like stromatolites are parallel with the crests of submarine sand dunes. Nearly all individuals, regardless of size, are streamlined by tidal currents. Many display higher growth rates on the side facing the incoming tide, which causes them to lean noticeably towards the clear water.

Many larger stromatolites have a soft botryoidal or pustular surface (Fig. 3*a*). Individual 1- to 10-cm-diameter botryoids are composed of uncemented ooid sand loosely bound by mucus and unidentified microbial filaments (Fig. 3*b*). Small stromatolites as much as 1 m high may also have a pustulate surface, but most are smooth and slightly elongate (streamlined) parallel to tidal currents. The surfaces of the small smooth individual are usually hard or crusty and lack the loosely held sand coating (Fig. 3*c*). Microbial filaments (Fig. 3*b*) occupy only the upper 2–4 m of the soft growth zone.

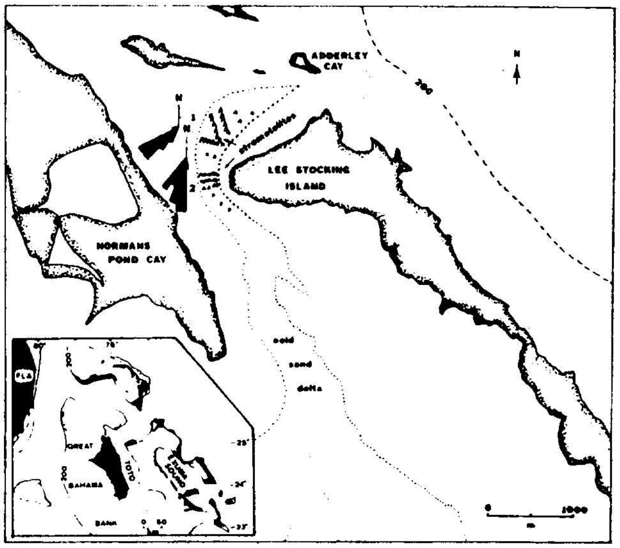

Fig. 1 Location of stromatolite-bearing tidal channel north and west of Lee Stocking Island, Exuma Cays, Bahamas. Rose diagrams are plots of the long axis of streamlined stromatolites that parallel the main axis of tidal flow in the channel: 1, 044–266° ($N = 31$); 2, 014–194° ($N = 60$). Orientation measurements of stromatolites were made with underwater Brunton at stations numbered 1 and 2. Visual observations demonstrate that many of the streamlined stromatolites are tilted toward the incoming tidal bottom currents. Contours in metres.

'Micro-atoll'-shaped stromatolites are also common. Micro-atolls are stromatolites with a central depression and an elevated rim, the central depressions being 10–30 cm deep and often filled with rippled oolitic sand. During maximum tidal flow, sand, shells and intraclasts swirl in the central depressions like pebbles in stream potholes. Whether the depressions are erosional features or are caused by growth of the rim has yet to be determined.

Where the channel turns southward (Fig. 1), the megaripples lose relief and the stromatolites become smaller. In this area the coalesced forms become S-shaped to form rows perpendicular to currents but with low relief, <1 m, and in plan view resemble Arabesque ornamentation. Circular micro-atolls interspersed with these shapes suggest they result from coalescence and erosion of semi-circular micro-atolls.

Staining experiments confirmed that stromatolites can grow rapidly. Three specimens were stained *in situ* with Alizarin Red S by injecting the solution into a clear inverted plastic bag cinched tightly around the base of each specimen. The bag and stain were removed after 6 h. Twenty-four h later, a layer of sand ~1 ooid thick (200 μm) had been deposited over the stained surface; sediment also adhered to vertical sides. Diver observation and underwater video documentation showed that most stromatolites are dusted with ooid sand during each tidal cycle and sand thrown against vertical surfaces by a diver sticks instantly to form a layer. A shell (*Strombus gigas*) from the base of a 50-cm-high specimen at a depth of 8 m gave a ^{14}C age of 480 ± 50 yr BP. The green alga *Batophora* sp., thought by Dravis[3] to be significant in stromatolite growth, was not found on the stromatolites studied here. The organic mat responsible for trapping suspended ooids and biogenic sands is a complex consortium of blue-green algae, specially adapted diatoms and as yet unidentified plants and organisms. The composition probably varies with season and time when buried columns are re-exposed. It is significant that the micro-ecosystem has adapted

Fig. 2 Two views of large aligned fence-like stromatolites. Note that the height of migrating rippled oolitic sand dunes (megaripples) just equals the height of stromatolites and hence periodically covers most stromatolites. Smaller stromatolites in foreground of upper photograph are populated by the green alga *Batophora* spp. *Batophora* is uncommon or absent from actively growing specimens, such as in Fig. 3*a* and *c*, and those recently uncovered by migration of oolitic megaripples and bars. Photo taken at slack tide at a water depth of 7 m.

to high-energy conditions with life forms having 'sticky flypaper' surfaces that trap sand grains, which, in turn, on stabilization, protect the mat from further bombardment by suspended grains.

In areas near the sides of the channels, ooid sands have been stabilized by marine grasses, and sand saltation does not occur. The stromatolites in these areas are densely populated by grazing fish and epibionts such as *Acetabularia*, *Batophora*, *Sargassum*, *Siderastrea* spp. and a variety of unidentified sponges and crustose calcareous algae. Most have been invaded by boring pholad clams, and the boring sponge *Cliona* spp. has attacked many specimens; these stromatolites appear to be relict forms that are being destroyed by bioerosion.

The internal structures of dissected columns are strikingly similar to Precambrian forms and consist of convex-upward laminations composed of ooid and pelletal sand. Laminae are caused by a combination of variations in grain size, cementation and alignment of pores. Some columns have incorporated siliceous spicules. The laminations occur in two styles: nested small-scale convex-upward laminations that form 1- to 4-cm-wide columns, and larger convex-upward laminations that encompass the large portions of columnar stromatolites (Fig. 4). The smaller columns, often separated by unlaminated cemented sand, are superimposed on the larger scale laminations. Many laminations thin towards the edges of the stromatolite and in places are truncated by near vertical wall structure along the sides of the more columnar stromatolites (Fig. 4). Larger stromatolites have not been sampled, but it is thought they may be composed of both small and large columns as much as 1 m high or more. The maximum synoptic relief determined by using any one lamina in the stromatolite structure (Fig. 4) is only 16 cm, whereas the total exposed relief of the structure itself is >45 cm; maximum synoptic relief of the small-scale column is <1-2 cm.

Voids are numerous, and whereas some are borings, others are constructional. Borings, whether excavated by pholads, serpulids, or sponges, are characterized by truncated grains and cement, and except for those made by pholads, they tend to be irregular in shape and orientation. Constructional voids are planar and parallel local laminations. Grains and cement are not truncated by constructional planar voids; these can form when fleshy epiphytes such as sponges and the alga *Batophora* sp. are entombed by subsequent deposition of laminated sand. The organism decays and a void, essentially parallel to depositional laminae, is formed and preserved by rapid cementation. Finer grained sand and silt may form geopetal fillings in both kinds of voids, which often contain uncemented ooids.

Marine cementation is rapid in this ooid-forming environment, and a portion of the Bahama Bank a few kilometres west of the Exuma Islands is where the process was first documented in the Bahamas[11]. Cementation of the stromatolites is similar to that in Shark Bay[12]. Uncemented ooid sand at the surface

Fig. 3 *a*, Actively growing stromatolites with soft pustulate surface. *Batophora* or other epibionts are absent from surface of actively growing stomatolites. White patch below hammer caused by scraping away the soft uncemented surface layer, which is held in place by microbial filaments. Sand thrown against vertical sides by diver will stick to form a layer ~1 ooid thick. *b*, Thin-section photomicrograph of growing uncemented upper surface of pustulate stromatolite. Note tiny microbial filaments (F) responsible for trapping of grains. Large grain is an ooid. Other grains are hard peloids. Note how filaments coalesce to form horizontal mat over growth surface (arrow). Growth of the internal filaments is normal to the surface. Section prepared by preserving pustule in ethyl alcohol, followed by desiccation in oven and vacuum impregnation with polyester resin. Specimen photographed under crossed polars using a gypsum plate to emphasize microbial filaments. Portion of ooid grain was plucked during preparation but algal mat shows original surface of the ooid. Scale bar, 200 μm. *c*, Underwater photograph of smooth surface of streamlined stromatolite which has been sawed with a hand saw. Note internal laminations, lack of pustules as shown in *a*, and lack of crenulations in convex-upward laminae. Ooid sand megaripple in background partially covered specimen 24 h later.

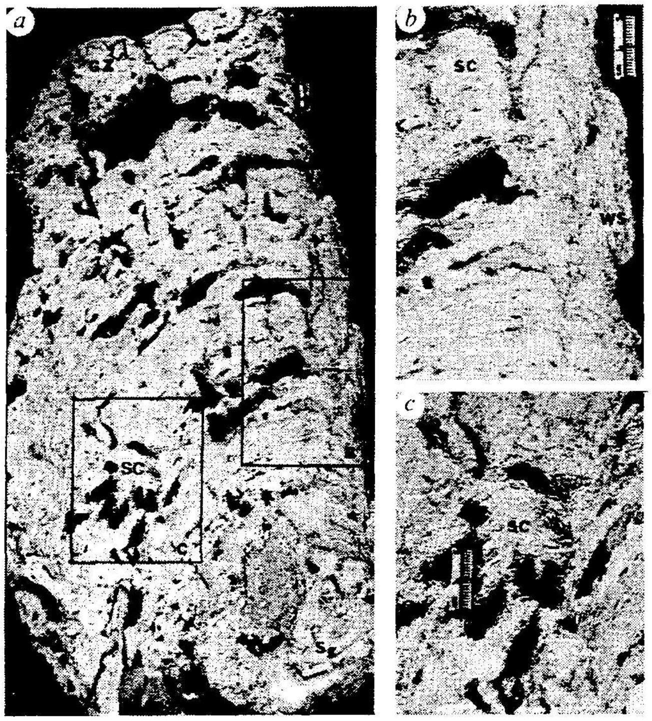

Fig. 4 Views of plastic-impregnated specimen which was cut in half to reveal internal structure. The slab is oriented so that incoming tide flowed from right to left. *a*, Slabbed plastic-impregnated specimen is 45 cm high and nucleated on a conch (*Strombus gigas*) shell (Sg). Note the small-scale convex-up laminations (SC) which form columns radiating from the base. Small-scale laminations are actually upward continuations of crenulations in larger scale laminations. Wall structure (WS) is shown in inset (*b*). Larger plastic-filled voids are borings; however, void around and below SC in inset (*c*) is thought to have been formed when a fleshy epibiont rotted away. GZ (top of *a*) shows soft uncemented pustular growth zone where grains are trapped and bound by the algal filaments shown in Fig. 3*b*. The small-scale columnar structure is thought to be caused by upward growth of pustules such as shown here. Unlaminated areas are former voids which have been filled with oolitic sand.

transitionally changes to hard limestone in the interior. The gradient from organically-bound sediment to rock extends from the upper surface to a depth of 4-5 cm and is best appreciated by sawing vertically into a stromatolite with a carpenter's hand saw; sawing begins easily but slows and becomes impossible beyond 30 cm as cementation increases.

The cement is mainly acicular aragonite, similar to that observed in other areas of marine cementation. In localized areas, aragonite crystals are tightly bundled to form what has been termed acicular fan druses[13] or botryoidal aragonite[14]; the latter occurs as a partial filling in voids. Micrite-textured Mg calcite is patchy and is more common in finer grained geopetal internal sediments. Magnesian calcite also occurs as cryptocrystalline cement in 20- to 25-μm-diameter tubules[3]. Because of their habit of penetrating both pore space and grains, Dravis[15] defined the tubules as chasmolithic/interolithic algae, probably of the genus *Ostreobium*. We are unsure of their actual affinity of the timing of their entry into the stromatolite matrix. They are not common in the uncemented growth zone and thus are not considered significant as primary sediment trappers. Additional study is needed to determine when and how they invade stromatolites and become diagenetically altered to micritic Mg calcite.

Bahamian subtidal stromatolites provide a new set of environmental parameters to use in interpreting spatial distribution of ancient stromatolites, orientation, water depth, salinity, constraints on growth forms and the timing of cementation and mineralization. For example, due to the Shark Bay modern analogue, most authors have regarded ancient stromatolites as intertidal in origin, although some have subtidal affinities or large size, which necessitated postulating enormous paleotidal fluctuations[8]. Modern subtidal stromatolites have been reported before[3,6,16,17] but unfortunately seem to have had little influence on the mainstream of geological interpretation. The Bahamian examples described here are by far the deepest and largest to be reported from the Holocene and hopefully may help clarify the many debates concerning salinity, current regimen, and depositional water depth of ancient stromatolites. Ancient stromatolites, like modern ones, were not limited to intertidal or hypersaline conditions, and many authors recognized this as a fact based on geological interpretation[8,18-20] The Bahamain stromatolites provide an alternative for palaeoenvironmental comparative studies.

In the Holocene and probably throughout much of Phaerozoic time, grazers and borers prevented stromatolite growth and preservation in normal marine subtidal waters. During the Precambrian, however, there were no known grazing and boring organisms, and stromatolites flourished uncontested for $>2\times 10^9$ yr. Without competition, Precambrian stromatolites freely populated enormous areas[20,21], and probably grew in water depths >10 m (ref. 8). Strong tidal currents were not a necessary requirement for growth and preservation in the Precambrian before the evolution of higher life forms. We anticipate that future comparative research on these Holocene stromatolites will provide many additional clues for interpreting depositional environments and the processes that moulded the shapes and distribution of ancient stromatolites of all ages.

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Geology of New Providence Island, Bahamas

PETER GARRETT *R.F.D. 2, Box 5115, Eames Road, Winslow, Maine 04902*
STEPHEN JAY GOULD *Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts 02138*

ABSTRACT

Contrary to the popular notion that the Bahama Islands are built of eolianite deposits, at least New Providence Island consists principally of elevated marine sand-flat and protected lagoon deposits. Narrow eolianite ridges separate such deposits from reef-tract deposits capped by prograding beach deposits on the northern (bank-margin) side of the island.

All exposed depositional phases are Quaternary. The most extensively exposed deposits we correlate with the ~125,000-yr high sea level, recognized world-wide. Elevations of keystone vugs in beach deposits of that depositional phase indicate paleo-mean sea levels of as high as +10 m.

Deposits of an earlier depositional phase suggest that there was then no island, but only a barrier sand shoal and reef tract. Holocene additions to the island's area have been minor and in the form of prograding beach deposits.

Classical superpositional stratigraphy has limited value in the elucidation of New Providence geology due to the nature of the deposits, which are partially overlapping thin facies sheets and lenses. Therefore, we have also used a morphostratigraphic approach and, as paleontological markers, species of *Cerion*, a very rapidly evolving genus of land snail. Limited radiometric dating is reported.

Islands on Bahama-type banks of earlier geologic periods were probably built almost entirely of beach deposits, rather than the eolianites and elevated marine deposits of which New Providence is built.

INTRODUCTION

During the past few decades, the Bahamas have been a focal point for studies of marine carbonate sedimentation. Many important principles have been developed in Bahamian waters, with minute description and ingenious explanation of key areas. At first, most studies were concerned with the origin of sedimentary particles and with the definition of facies (Illing, 1954; Newell and Rigby, 1957; Newell and others, 1959, 1960; Purdy, 1963a, 1963b; Storr, 1964). Later, when cores were taken, sedimentary structures were described, and the third dimension fleshed out our understanding of bank-top facies (Imbrie and Buchanan, 1965; Ball, 1967; Shinn and others, 1969). Most recently, seismic-reflection profiling combined with coring and isotopic dating have extended descriptive-interpretive studies into the realm of the fourth dimension (Hine and Neumann 1977; Hine and others, 1981; Beach and Ginsburg, 1980).

Ironically, in the context of so much geological productivity, little attention has been focused on the islands. It is true that Young (1972, and *in* Little and others, 1973) discussed the application of facies analysis to landform studies on the larger Pleistocene-rock islands, and Harris (1979) analyzed the sedimentary and diagenetic evolution of a late Holocene sand cay. No map, however, has yet been published for the basic stratigraphic geology of a Bahamian island (although several sketch maps exist: of San Salvador by Garrett, Bimini by T. P. Scoffin, and Chub Cay by D. C. Pasley, all unpublished).

This bias of studies toward the marine Holocene is somewhat surprising, in view of the fact that diagenetic clues often suggest the presence of islands on ancient carbonate banks (Dunham, 1969; Badiozamani, 1973), even though there may be no evidence from sedimentary structures.

To be fair, the geology of a Pleistocene carbonate island (sedimentology, stratigraphy, and diagenesis) is well known through work on Bermuda (MacKenzie, 1964a, 1964b; Land and others, 1967; Land, 1967, 1970). Bermuda is similar in many respects to some Bahamian islands, especially those facing the open Atlantic, but there are significant sedimentologic differences between Bermuda and New Providence.

Bahamas and New Providence: General Information

The Bahama Banks are well known as examples of crustally stable subsiding carbonate platforms (Lynts, 1970; Meyerhoff and Hatten, 1974; Mullins and Lynts, 1977). Evidence from a deep borehole on North Andros Island (Fig. 1, crossed circle symbol) shows that the rate of subsidence has varied between 48 and 18 m/m.y. during the Tertiary (Lynts, 1970).

In general, the Bahama Banks have slightly elevated wave- and tide-washed rims surrounding more protected lagoons. The rims were reef-dominated earlier in the Pleistocene (Cant, 1977; Beach and Ginsburg, 1980, 1982) but are now for the most part elevated by the accumulation of sand in shoals (Ball, 1967; Hine, 1977; Harris, 1979), some of which bury early Holocene reefs (Hine and Neumann, 1977; Hine and others, 1981). The most important types of shoals are marine sand belts, usually of oolitic or skeletal sand, and beach-dune complexes. In the protected lee of these rim sand bodies, the lagoons are chiefly shallow (less than 10 m) plains, covered with pellet and grapestone sands mixed with varying amounts of carbonate mud and thoroughly bioturbated.

New Providence lies at the northwest corner of the dissected eastern Great Bahama Bank, known locally as Yellow Bank (Fig. 1). The island's setting is unusual in two respects: first, because most Bahamian islands are situated on the eastern (most windward) margins of their banks, and, second, because the two other prominent northwest corners of banks in the northern Bahamas have topographically low margins. Hine and others (1981) suggested that because the northern margin of the Great Bahama Bank was topographically low, the initial rapid Holocene rise in sea level (2.8 m/1,000 yr) precluded development of an island and reef rim on that margin. Clearly, antecedent topography is of primary importance (a point made several time below); however, what the pre-Pleistocene or early Pleistocene antecedent topography of New Providence was like is not known and is not discussed in this paper.

Like most Bahamian islands, New Providence has two contrasting coasts. Its northern and western coasts are within 1 to 5 km of the steep drop-off to the North East Providence Channel and the Tongue of the Ocean, both deep submarine troughs. In contrast, its southern and eastern coasts slope off very gently onto the submarine plain of Yellow Bank. Owing to these contrasting coasts, the terms "windward" and "leeward"

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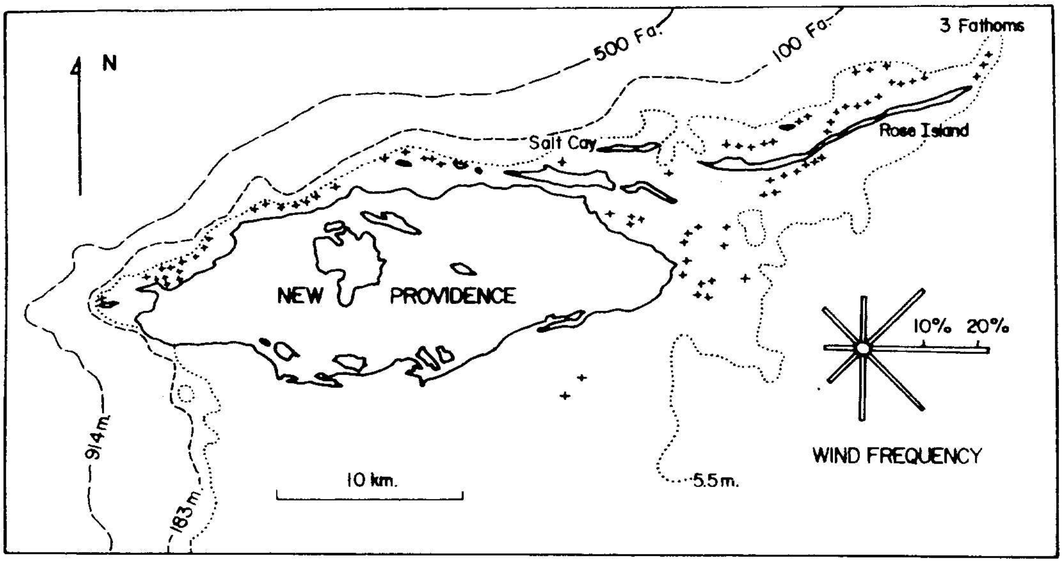

Figure 2. Bathymetry around New Providence and adjacent islands (from Hydrographic Office chart no. 26300). Note (a) proximity of the bank margin to the island's north and west shores, and (b) a major reef tract to the north and the many patch reefs to the east (reefs marked +). Wind data from U.S. Naval Weather Service Command (1974).

can have no connotations of exposure or protection to or from prevailing winds. Reference to Figures 1 and 2 shows that the northern coast can be classified as windward because it is subject to swells and northerly winds directly from the Atlantic and (with less fetch) across the North East Providence Channel. The eastern coast, however, even though it is more truly windward, is a protected coastline, due to the width of the Yellow Bank.

STRATIGRAPHIC CRITERIA AND METHODS

The customary method for establishing a stratigraphic section relies on the venerable principle of superposition. Different formations are distinguished from each other in a vertical section, with changes in fauna, changes in facies, or erosion surfaces used as planes of separation. Given that superpositional evidence is meager on New Providence, we have had to rely heavily on other criteria.

Discontinuity Surfaces

In Pleistocene limestones, the most common planes of separation are "discontinuity surfaces." Such surfaces are recognizable by the presence of soil crusts, soil breccias, diagenetic soilstones, blackening of clasts in the soil breccias, rhizomorphs (root casts), and reddening of the rocks at or just below the discontinuity surface. Perkins (1977) discussed the recognition of such surfaces at length. In view of the fact that discontinuity surfaces in the Bahamas are similar to those described by Perkins from south Florida, we shall not describe them further here.

We know only 13 localities on New Providence (from about 250 examined) where discontinuity surfaces can be seen in outcrop. Nonetheless, these localities form a major basis for our stratigraphic subdivision. At most of these localities, two eolian units are separated by entirely subaerial discontinuity surfaces; however, at 5 of the localities, the soily nature of the discontinuity surface has been modified by marine processes, specifically, bioerosion and rolling of clasts.

Cerion Faunas

The exposed Pleistocene deposits of New Providence Island probably span only a few hundred thousand years at most. This time is too short for almost any paleontological resolution; animals, particularly marine invertebrates (the bulk of the fossil record), do not evolve fast enough to exhibit any consistent changes over such short periods of time. This failure of paleontology represents a primary reason why the most basic stratigraphic geology has not heretofore been elucidated for any Bahamian island.

Dune deposits of the Bahamas, however, are blessed with abundant fossils of a very unusual animal, the land snail *Cerion. Cerion* may be one of the most rapidly evolving of all animals (Mayr and Rosen, 1956; Mayr, 1963). Snails of this genus are currently divided into some 600 species (Clench, 1957; Gould and Woodruff, 1978). Not all are technically valid by any means, but the names have been given to recognizably different morphologies, and their sheer number illustrates the incredible diversity of this genus. *Cerion* evolves so rapidly that a few hundred thousand years may witness the passage of several distinct faunas. Thus, thanks to the unusual evolutionary vigor of *Cerion*, we have been able to use paleontological criteria for establishing the stratigraphy of New Providence Island.

We have found three sequential *Cerion* faunas in dune deposits of New Providence Island (Fig. 3). (We do not claim that each evolved directly into the next. Most transitions probably reflect the local extinction of one fauna and the immigration of the next. Faunas were often extirpated locally at times of high sea level, whereas lowered sea levels connected previously separated islands and engendered periods of migration; Dall, 1905; Gould, 1971). The first fauna, found in deposits of our phases IB and IC (see "Stratigraphic Succession" below), includes a distinctive unnamed species of *Cerion*, here called *Cerion sp.* It is large, relatively tall and delicate, and finely ribbed. The second fauna, the common cerions of phase II, includes two species: the large, smoother or coarsely ribbed, thick-shelled, roughly triangular *Cerion agassizi*, and the barrel-shaped dwarf, *Cerion universe.* The third fauna, found in Holocene deposits of phase III, contains *Cerion glans*, the most common species living on New Providence today.

Without exception, this paleontological sequence matches patterns based on other criteria of superposition, geomorphology, diagenesis, and radiometric dates. For example, all dunes identified as Holocene by diagnetic grade, absence of soil crusts, and ^{14}C date (see Phase III Deposits below) contain *C. glans.* Furthermore, all cases of direct superposition between units separated by discontinuity surfaces contain either *C. agassizi* in both units or *Cerion sp.* in the lower unit and *C. agassizi* in the upper unit.

Morphostratigraphy

This is a method, first used by Frye and Willman (1962), that utilizes geomorphic reasoning to unravel a succession of landforms. Our geomorphic reasoning for unraveling the Pleistocene succession of New Providence is derived by analogy with Holocene sedimentary environments common in the Bahamas.

One such simple case is of a prograding beach (Fig. 4A). Older beaches occur to landward,

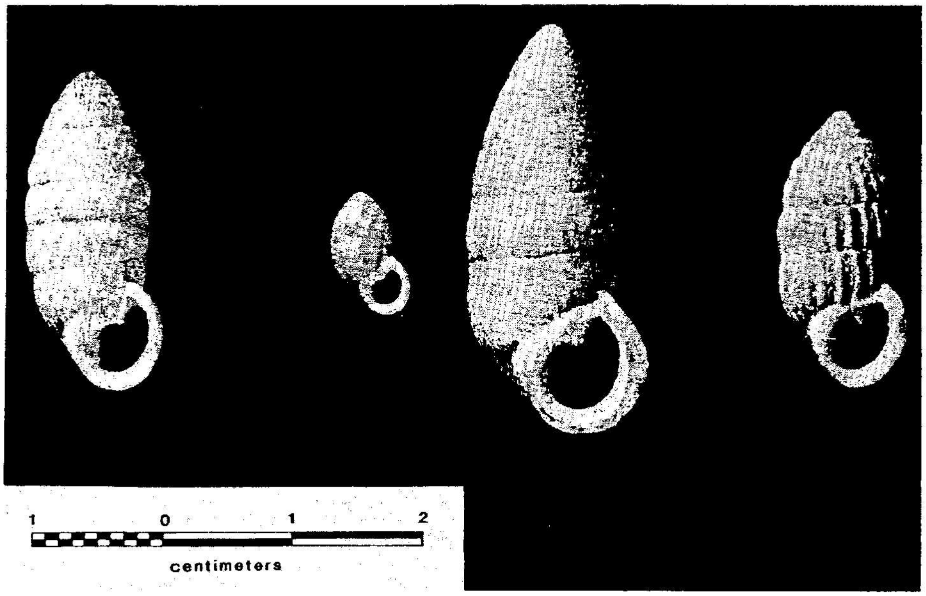

Figure 3. The three *Cerion* faunas of New Providence. Left: *Cerion sp.* from phase IB dunes at Gambier. Middle: *Cerion agassizi* (large specimen) and *Cerion universe* from the Nassau ridge, phase II. Right: *Cerion glans* from Holocene (phase III) dunes at Xanadu (Old Fort Beach).

partly buried by younger sands (Fig. 4A, x–x'). This stratigraphy is no different from that employed on Bahamian Holocene shorelines (Lind, 1969) and in the Pleistocene dune sequence of Bermuda (Land and others, 1967). We thus assume as an initial working hypothesis that the more landward beach/dune ridges are older.

There are exceptions to this generality. A considerably higher sea level could overtop the original beach/dune ridges and deposit younger ridges landward of them. In such a case, however, the form of the younger deposits would probably be modified by submarine topography developed on the older ridge. Common cases of modification of beach/dune geomorphology by pre-existing topography are illustrated in Figure 4A. Most pre-existing topography in Bahamian beach/dune settings is derived from cemented (Pleistocene or Holocene) dune ridges. When emergent, headlands on the ends of such ridges can serve as anchors for catenary[1] beaches. These catenary beaches curve landward from the headland and are easily recognizable as being younger than the headland.

Reefs frequently grow on submerged Pleistocene dunes also, and they can produce a similar type of modified beach/dune geomorphology, through the growth of a tombolo. In such a case, the beach becomes catenary in form as it progrades (Fig. 4A).

Figure 4B illustrates a third type of morphostratigraphy. Such a situation may arise when a narrow gap exists between two cemented dune ridges. The gap becomes a tidal channel and emergent sand shoals develop on the margins of the tidal channel, or as shallow banks or tidal flats bankward of the island. Such topography is now characteristic of the Ragged, Exuma, and Berry Island groups in the Bahamas. Harris (1979) showed how it can develop even within one depositional phase.

Ancient Sea Level

We used keystone vugs (Dunham, 1970) in beach deposits to estimate sea levels of deposition throughout New Providence. The method is based on the observation that, in modern beaches, keystone vugs occur in the upper beach-face deposits, above mean tide level (Hoyt and Henry, 1964; P. Garrett and H. L.

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[1] Catenary: literally, in the form of a hanging chain. In the context of beaches, the form hangs (curves) between two anchoring headlands.

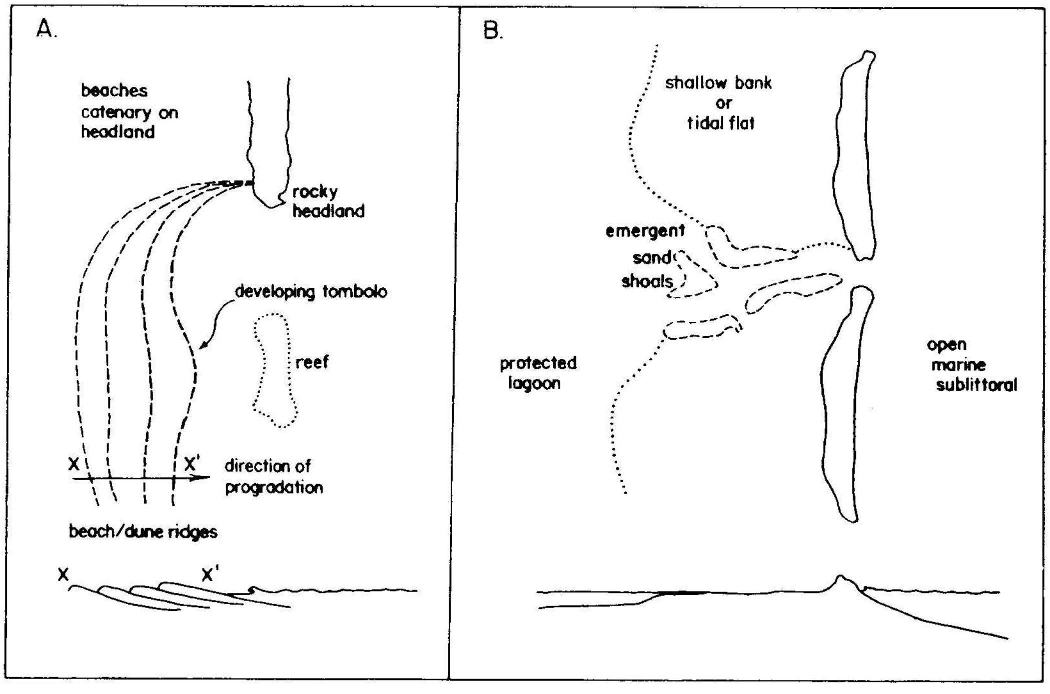

Figure 4. Cases illustrating the morphostratigraphic principles used in this study. A. Section x-x' cuts through prograding beach ridges (or dunes), the youngest of which are to seaward. However, the entire dashed sequence is clearly younger than, even though landward of, the rocky headland. Such curved beaches are termed "catenary" in this paper (see text). B. A more complicated morphostratigraphic situation, in which the sand shoals and shallow banks are clearly dependent on the protection afforded by the islands, or the funneling of tidal currents through the interisland channel. The islands must therefore predate or be contemporary with such shoals and banks.

Vacher, unpub. data). This is so regardless of the degree of exposure of the beach, which later affects only the relative thickness of the beach-face deposits, or the prevalence of keystone vugs in beach deposits. In the Pleistocene facies of New Providence, all associated sedimentary structures confirm this interpretation.

Thus, we estimated sea level of deposition at the lowest level of keystone vugs in beach-face deposits. Elevations were measured by hand level and metre stick, using the Bahamas Department of Lands and Surveys 1:2,500 scale series of topographic maps (with contours at 2-ft intervals) as a base.

Sea level of deposition, we think, cannot be used as a very reliable indicator of stratigraphic position, because any particular sea level could have been reached any number of times during the several oscillations of the Pleistocene ocean. In addition, deposition could, and probably did, take place over a range of sea levels during a single interglacial "highstand."

Despite these reservations, we have used sea level of deposition as a stratigraphic marker where all else failed, but then only in the case of one unit, for which independent evidence supported that use. In brief, our *Cerion* stratigraphy supports the view that sea levels were higher than +4 m during one depositional phase only (identified below as phase II).

Unless otherwise noted, sea levels of deposition are corrected for subsidence of the Bahama Banks (Lynts, 1970).

Petrography

All 250 localities examined during the geological mapping of New Providence were sampled for hand-specimen determination of lithology, in order to get some feel for the areal extent of constituent grain types. Most of the Quaternary rocks of New Providence are grainstones, so simple division into skeletal, peloidal, or oolitic lithologies was possible. In addition, about 20 thin sections of rocks at critical localities were examined.

Petrography could not be used as a tool for correlation of units, although we did find that, within a limited distance, units that correlated on other bases usually had similar constituent particle compositions.

Radiometric Dating

Corals were collected wherever possible for dating by the ^{230}Th/^{234}U method, but without exception all were too calcitized to yield reliable dates.

One shell sample was dated by ^{14}C.

STRATIGRAPHIC SUCCESSION

The stratigraphic succession of exposed strata on New Providence is here divided into phases, numbered I, II, and III. Deposits of each are first described; then points of paleogeographic or chronologic significance are discussed separately.

Phase IA Deposits

Only two localities (1 and 2 in Fig. 5A) serve to define phase IA. Locality 1[2] is a murky pit of unknown depth (probably 10 m below the water table). From this pit, below the near-surface strata (phase IB) and below a well-developed soil crust, samples have been dredged of a variable succession of very fossiliferous sediments, all substantially recrystallized to calcite. They include boundstones crowded with sticks of the red alga, *Goniolithon.*

Locality 2 is a pit 350 m long that is filled with water clear enough to permit examination by divers. The top of the section includes several units of burrowed marine facies separated by discontinuity surfaces. These were doubtless deposited in a relatively protected lagoon behind a barrier (and they probably belong to two or all of phases IB, IC, or II; see below). At a depth of 6.5 m, however, lies a single set of foresets that are 1.5 to 2 m thick and clearly of marine origin, because there is an abundance of coarse skeletal

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[2] Numbered localities mentioned in the text are especially important stratigraphically. They are listed and located in Table 1.

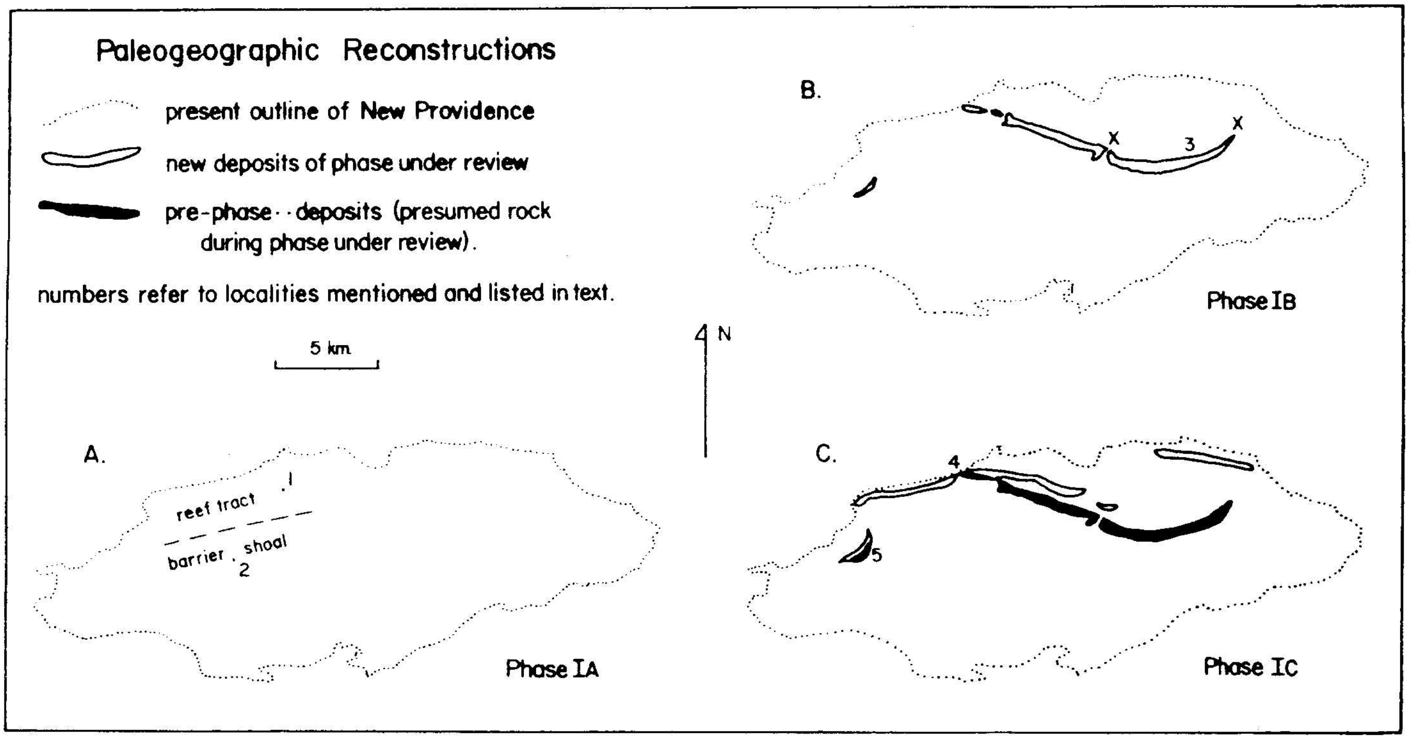


Figure 5. A. Paleogeography during phase IA deposition. B. Paleogeography during phase IB deposition. The first eolian ridge islands are built. X indicates presumed older rocks or contemporary reefs on which the ridges are catenary. During the deposition of eolianite ridges, the surrounding areas were probably a marine-flats facies (bankward) or a reef tract (seaward). C. Paleogeography during phase IC deposition.

TABLE 1. LOCALITIES MENTIONED IN TEXT OR FIGURES

	Grid reference*
1. North Killarney borrow pit	545 738
2. Windsor Field borrow pit	518 705
3. East Street cut	637 715-8
4. The Caves	525 746
5. New Providence Development Company silage pit (obtain permission from NPDC)	478 704
6. Lyford Cay, Western Road west cut (obtain permission from Lyford Cay Company)	443 695
7. Queen's Staircase	642 749
8. Behind Clarence A. Bain Government Offices, Thompson Boulevard	620 733

*Permits location, to within 100 m, on maps available from Department of Lands and Surveys, Nassau, Bahamas.

material on the slip faces of the foresets. These foresets are planar avalanche sets (Imbrie and Buchanan, 1965) and dip approximately north. They are visible at both ends of the pit and are therefore part of a sizable sedimentary deposit.

Discussion of Phase IA

The *Goniolithon* rock of locality 1 is a significant occurrence, because *Goniolithon* boundstones are characteristic of the inner reef tract in both south Florida (Enos, 1977) and Andros (Gebelein, 1974) and are unknown in bank-interior environments. As locality 1 lies bankward of the first (phase IB) eolian ridge, the *Goniolithon* rock must belong to a phase of open circulation in the New Providence area. The thick submarine foresets of locality 2 probably represent a submarine sand-shoal barrier. These two pieces of evidence yield the sketchy paleogeographic map of Figure 5A, which assumes that both deposits are part of the same depositional phase.

Phase IB Deposits

Phase IB initiated the development of eolianite dune ridges (Fig. 5B). All dunes yield specimens of *Cerion sp.*, the oldest *Cerion* fauna. The deep road-cut of locality 3 reveals thick foresets and backsets, but no discontinuity surfaces within the phase IB dune. The southerly dip of the foresets indicates that source beaches lay on the northern side.

Phase IC Deposits

A second set of dune ridges developed during phase IC (Fig. 5C). At localities 4 and 5, eolian sands of this phase lap against phase IB dunes with a red discontinuity surface between. *Cerion sp.* is also present in phase IC deposits.

Discussion of Phases IB and IC

Phases IB and IC are paleontologically identical. Were it not for exposed discontinuity surfaces and the separation of dune ridges in central and eastern New Providence, we could not distinguish between them. We suspect that they may represent deposition during two succeeding high stands within one long period of generally high sea levels.

Although we have chosen to lump phase IA with phases IB and IC, it is possible that phase IA may represent a considerably earlier marine phase.

Note that the easternmost ridge of phase IB is catenary on two nodal points (marked X in Fig. 5B). Such nodal points were probably rocks awash during phase IB deposition; originally, they could have been phase IA reefs.

Phase II Deposits

Most of the island's deposits fall within this depositional phase. The pattern and timing of sedimentation are very complex, and owing to lack of adequate exposure, we have not been able to sort out the complexities into separate subphases. All the deposits of this phase fit into a single biostratigraphic zone, that characterized by *Cerion agassizi*, with or without *C. universe.* Yet, one locality (6 in Fig. 6) displays at least six depositional events (units i–vi of Fig. 6) within this single zone, each separated from the others by discontinuity surfaces.

To simplify the discussion, we treat phase II sedimentation in the framework of two facies provinces. All phase II localities and place names appear in Figure 7. Figure 8 gives our paleogeographic reconstruction.

Phase II: Northern Eolian Ridge and Related Facies. Locality 6 (west end of New Providence; see Fig. 6) illustrates the major facies variants of the northern ridges. All six units are at least partly eolian, steep foresets and more gently dipping backsets making up the bulk of the deposits. In this and their general morphologic expression, they are similar to the eolianites of Bermuda (Mackenzie, 1964a). The southerly dip of the foresets indicates a source of sand to the north. Units ii and iii are beach-dune complexes in which the beach-to-dune transition is well displayed. Backsets grade down and northward into low-angle beach foreshore sets with keystone vugs. The fact that supply beaches grade directly into dunes indicates that these dunes were tied to their supply beaches and did not migrate inland. In this respect, they are also similar to the eolianites of Bermuda (Bretz, 1960; Land and others, 1967). Poorly defined stratification and abundant rhizomorphs and

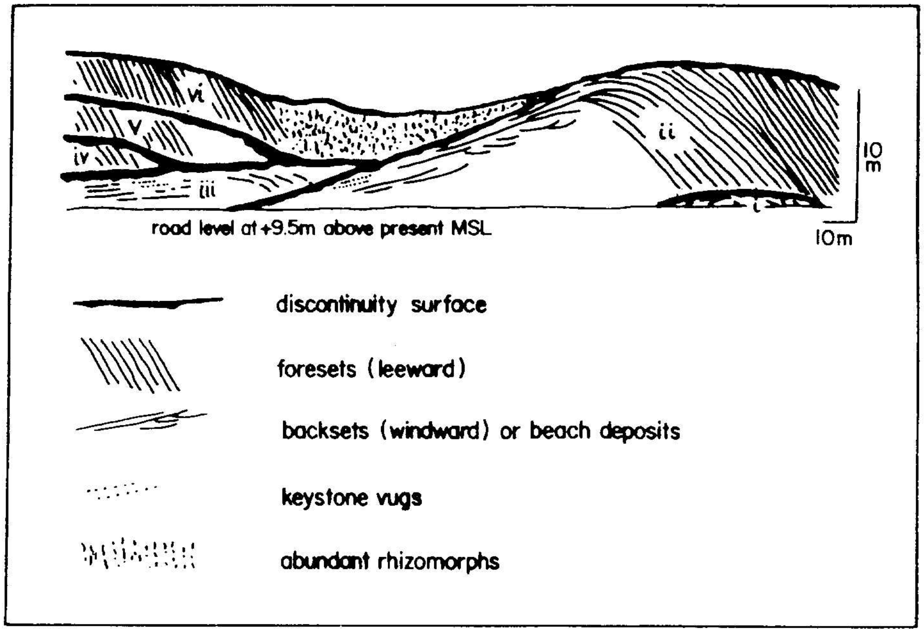


Figure 6. Locality 6. Simplified field sketch, showing stratigraphic and sedimentologic relationships between the six units exposed, all of which are paleontologically within phase II, but each of which is separated from the others by a discontinuity surface, with paleosols. All six units are at least partly eolian, with foresets dipping more or less south. The eolian portions of units ii and iii, however, are transitional northward into low-angle beach sets with keystone vugs. Note that the simple morphostratigraphic sequence of Figure 4A (x-x') cannot be followed here. For example, unit vi oversteps units v, iv, and iii, and unit ii oversteps unit i. All that can be said morphostratigraphically (that is, if there were no road-cut here) is that unit vi is younger than unit ii. Owing to such complications and to our inability to correlate units paleontologically, we have not been able to subdivide phase II.

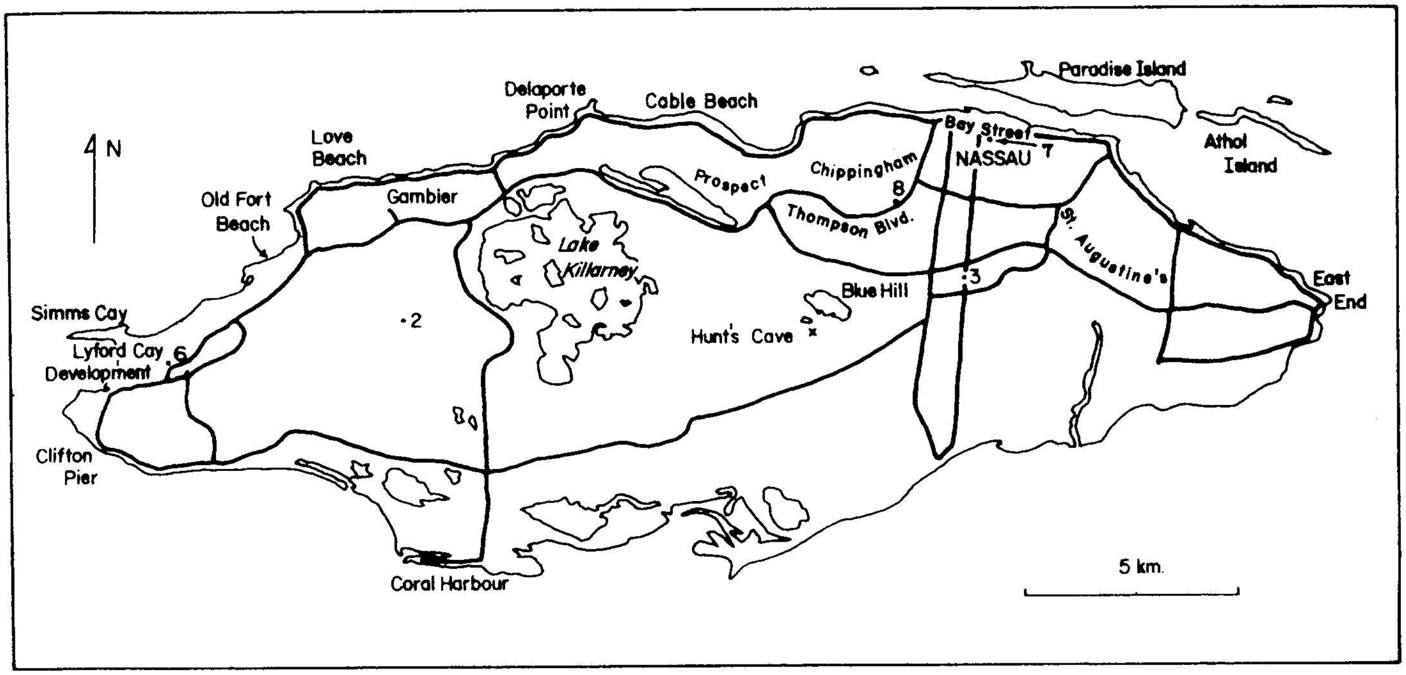


Figure 7. Place names and important localities on New Providence mentioned in the description of phase II and phase III deposition. Only major roads are shown. Localities are numbered and listed in Table 1.

Cerion shells in parts of these eolianites attest to the presence of vegetation during development.

South from locality 6 toward Clifton Pier, splayed ridges abut the modern coastline at right angles. The elegant coastal sections at Clifton Pier demonstrate that this splayed-ridge topography arose by progradation to the west of a series of spit accretions (Ball, 1967, p. 583–585). However, there are no discontinuity surfaces between any of the separate spit-accretion ridges. All the ridges thus could be equivalent to one of the units at locality 6; morphostratigraphy does not help in correlation here.

North of the Gambier eolian ridge, several coral patch reefs are exposed with their level tops 1 m or so above present mean sea level (MSL). They are all surrounded and partly buried by prograded beach sands, capped in one case by eolian facies with *Cerion agassizi.*

Extending south from the west end of the Gambier ridge is a spit-accretion sequence somewhat similar to that at Clifton Pier. It consists of coarse cross-bedded sands with intraclast blocks, capped by beach facies, and built up into a low dune. The growth of this spit must have effectively isolated the reef tract to the north of the Gambier ridge from the lagoon to the south (see Fig. 8).

The bulk of the Nassau ridge is phase II eolianite, with one prominent discontinuity surface displayed at locality 7. To the west of the Nassau ridge, there are examples of both of the morphostratigraphic situations illustrated in Figure 4. The Thompson Boulevard eolian ridge was the first to develop, catenary on the Nassau ridge. It was followed by the Chippingham-Prospect ridges. Between the two latter ridges, there was a narrow tidal pass (TP of Fig. 8) that allowed the development of a sizable marine sand shoal back of the Chippingham ridge and between it and the Thompson Boulevard ridge. At locality 8, shoal deposits overlie the Thompson Boulevard ridge, with no sign of a case-hardened contact. Thus, the shoal was deposited in the same depositional phase as the underlying dune. Confirming evidence is provided by the presence of *Cerion agassizi* in both the north and south ridges and in eolian patches atop the shoal. After shoal development, the tidal pass was sealed by prograding beaches to the north of the Chippingham ridge. Eolian patches in these also contain *C. agassizi.*

Eolian and beach ridges built and prograded, initially catenary from the eastern end of the Nassau ridge, but eventually to the north and northeast of New Providence. These ridges can be divided morphostratigraphically and paleontologically into two series.

The first series that prograded from the Nassau and St. Augustine's ridges out to north Paradise Island and east Athol Island bears the normal phase II *C. agassizi* fauna. The second series is initially catenary on dunes of the first series, for example, at west Paradise Island and west Athol Island. The last dunes in this series are the ridges of Salt Cay and Rose Island (see Fig. 2). The *Cerion* faunas in the deposits of the second series, too few in number and too fragmentary to permit certain identification, are smaller than any *C. agassizi* and may be hybrids between *C. agassizi* and *C. universe.* In other respects, they resemble the modern species *C. glans,* also found in Holocene deposits (phase III).

A prograding beach facies that occurs among the first series dune ridges in and around Nassau was cored by the Bahamas Public Works Department in a series of boreholes along Bay Street. The cores reveal that 3 m of beach-face facies overlies 8 m of sublittoral planar and cross-bedded sands. These in turn overlie bioturbated, poorly sorted sands or enclose patch reefs (Fig. 9A).

Phase II: Southern Protected Lagoons and Marine-Flats Facies. The northern eolian ridges of New Providence all lie approximately parallel to the bank margin. At Clifton Pier, however, the bank margin runs south along the Tongue of the Ocean (see Fig. 2), whereas the ridges in the southern part of the island strike off to the east (Fig. 8).

These southern ridges differ from the northern ridges in several ways. They become younger to the south or southeast, and they overlie, are surrounded by, and derive their sediment from an extensive marine-flats facies.

The marine flats are characterized by well-burrowed sandy deposits in generally level terrain. Burrows of thalassinoid shrimp (ichnogenus *Ophiomorpha*) are particularly common, as are shells of *Lucina pennsylvanica* (Hebard, 1967). The top few decimetres of sediment are commonly bedded.

The development of the southern ridges can be interpreted from their internal structure

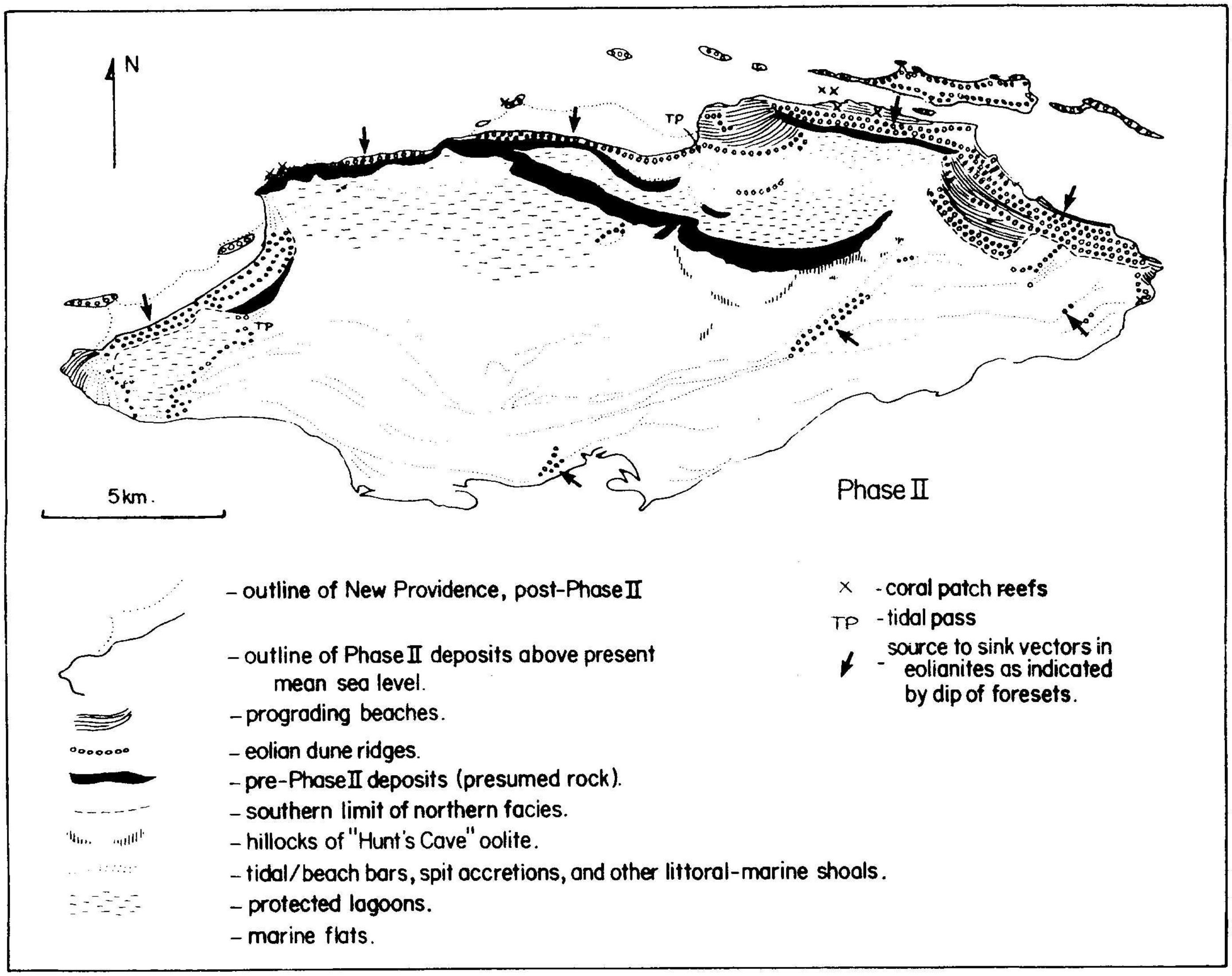


Figure 8. Paleogeography during phase II deposition.

(Fig. 9B). They began as slightly elevated sandbars in the shallow waters of the marine-flats environment. The sandbars were washed and sorted by tidal ebb and flow producing bidirectional cross-sets. With time, many grew into a beach environment; thus, we refer to them as tidal/beach bars.

These tidal/beach bars faced the open waters of Yellow Bank in several southerly directions. Only when they faced to the southeast—that is, more nearly perpendicular to the prevailing winds (Fig. 2)—did they develop narrow eolianites on top (with foresets dipping to the northwest). Where they faced southwest—that is, around the southern end of Lake Killarney—many are not even capped with beach facies.

Lithologically, the marine-flats facies, with its tidal/beach bars, is dominantly oolitic to the west but is pelletal in the eastern quarter of the island. Near the center of the island, however, there is a group of distinctive oolitic hillocks deposited as subtidal/beach/dune facies, which we map separately as the Hunt's Cave oolite in Figure 8. Hunt's Cave itself has a noteworthy geologic history (Fig. 10). Following deposition of the oolite at a sea level of about +7 m, a cave was cut, probably by karst, and filled with dripstone. Later, the dripstone was eroded, and the cave was enlarged, apparently by marine erosion at a second sea level of about +7 m.

Paleontologically, the presence of *Cerion agassizi* in two small dunes capping tidal/beach bars near the east end of the island ties the deposition of both tidal/beach bars and marine flats to phase II time.

Several protected lagoons lay between and immediately south of the northern eolian ridges; all were floored with fine bioturbated pellet wackestones. They are characterized by a special fauna, usually of small mollusks, including cerithiids in places, and abundant benthic forams.

The small lagoon lying northeast of Clifton Pier must have been almost totally enclosed, with perhaps one tidal pass on the east (TP in Fig. 8). The considerably more open lagoon in the Lake Killarney area must have become more isolated by two depositional closures during phase II. One was the spit accretion southeast of Gambier; the other, the southerly ring of tidal/beach bars around Lake Killarney. The lake itself is only 1 m deep at its deepest, and its position suggests that it now floods the original saucer-shaped depression of the phase II lagoon.

Few excavations are deep enough to penetrate the blanket of phase II lagoon and marine-flats facies. At locality 2, we see that the phase II marine flats overlie two similar facies blankets,

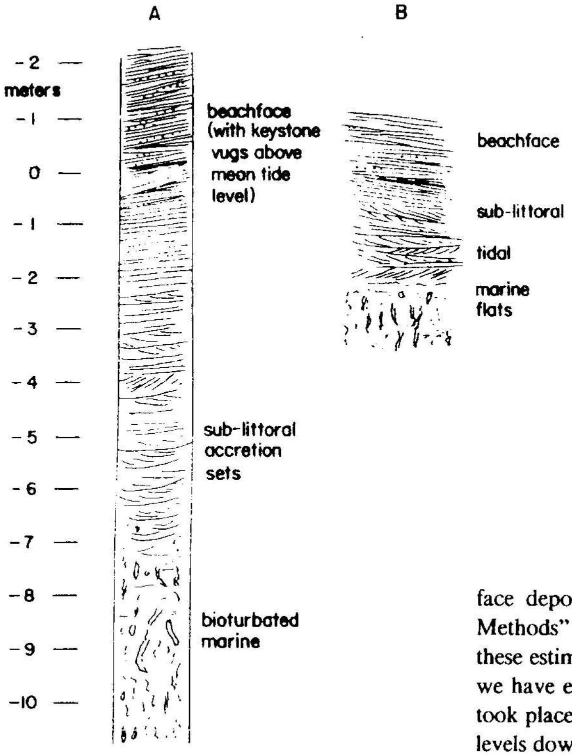


Figure 9. Facies characteristic of: A. The prograding beach facies of the northern, exposed side of New Providence (sketched from cores taken along Bay Street, Nassau). B. Tidal/beach bars of the southern, protected side (sketched from outcrop). Note that several groups of sedimentary structures are common to both situations but that the thickness of each package is markedly less in the protected situation. Zero metres on the scale is inferred to be paleo-mean sea level for both A and B.

separated from each other by discontinuity surfaces. Lacking contrary evidence, we tentatively assign these buried marine flats to phases IB and IC.

Discussion of Phase II

Two aspects of phase II deposition deserve additional comment: (1) dating and (2) sea levels of deposition.

Our efforts to date phase II deposits have been singularly unsuccessful. We gathered corals for dating from patch reefs near Gambier, from reefs exposed by the dredging of Nassau Harbor, from the buried reefs in the Bay Street (Nassau) cores, and from a patch reef near East End. However, all were too calcitized for reliable dating by the ^{230}Th/^{234}U method (W. S. Moore, 1980–1981, personal commun.). Thus, our only available coral date is sample 36-C of Neumann and Moore (1975) from the spit-accretion sequence at Clifton Pier. This sample was dated at $(146 \pm 9) \times 10^3$ yr.

Richard Mitterer (University of Texas at Dallas) measured amino-acid racemization ratios for us on *Cerion* shells from paleosols through the deposits of locality 6 (Fig. 6). Unfortunately, however, with no coeval corals to radiometrically date the same deposits, such ratios cannot be calibrated as dates.

There are many phase II localities on New Providence where sea levels of deposition can be reliably estimated, using keystone vugs in beachface deposits (see "Stratigraphic Criteria and Methods" above). Figure 11 gives the results of these estimates. The highest sea levels for which we have evidence lay at +10 m, but deposition took place at some point on the island at all sea levels down to below present MSL.

In the southern area (Fig. 11), the beach portions of the tidal/beach bars show some interesting sea-level relationships. The first is that no single bar was elevated as a beach all along its length at the same sea level; variations of as much as 2 m occur along any one bar. The second is that, in general, the northern bars were deposited at the highest sea levels (maximum +8.8 m), but at the south coast, the beach bars were deposited at lower sea levels. Because our morphostratigraphy establishes the northern bars as older, the sequence of tidal/beach bars, traced south, was deposited during a recession of sea level. Another example of deposition during receding sea levels is the spit-accretion sequence at Clifton Pier. There, one of the central ridges is capped by beach deposits at +8 m, but four ridges and 400 m to the northwest, sea level contemporary with the beach facies was less than +4 m.

The Hunt's Cave oolite may record two episodes of phase II sea levels at +7 m, one for its deposition and another for the cave cutting, but neither episode is datable at present.

Phase III

Most phase III deposits (Fig. 12) are uncemented skeletal sands, although some are lightly cemented beachrocks and dunes in which Mg-calcite still remains and on which there are no soil crusts developed. The eolian deposits contain the modern species *Cerion glans*.

Along the northwest shore of New Provi-

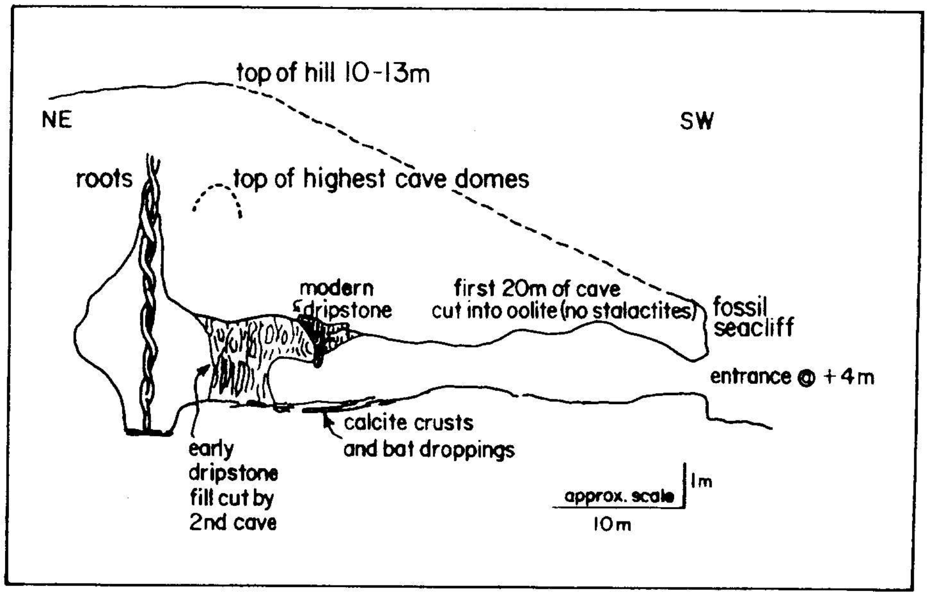


Figure 10. Schematic geology of Hunt's Cave (for location, see Fig. 7). The hillock is a deposit of oolite, and bedding indicates subtidal, beach, and dune facies, deposited at a sea level of about +7 m. The first cave was cut, then filled with dripstone. Later, the southern side of the hillock was cliffed, the cave enlarged, and the dripstone eroded, at a second sea level of +7 m. Modern dripstone is developing from the cave ceiling. (The +7-m elevations are corrected for 3 m of subsidence in 125,000 yr (Lynts, 1970). Elevations on the figures are relative to modern sea level.

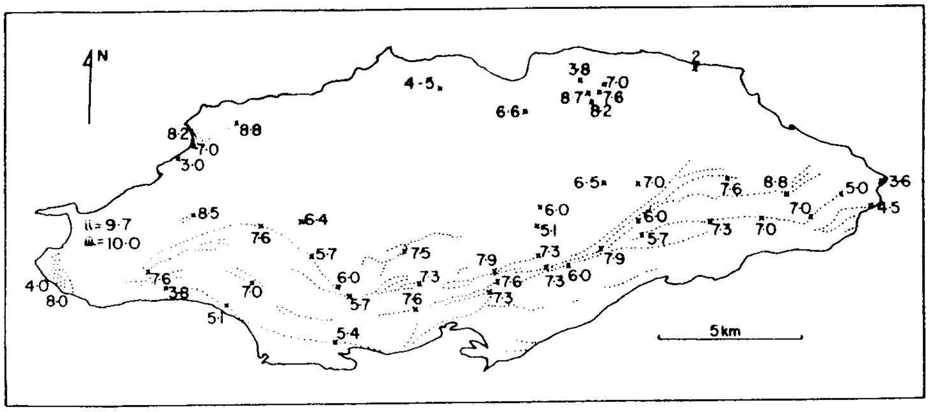


Figure 11. Phase II sea levels, estimated at the lowest level of keystone vugs in beach facies. Data are from outcrops in road-cuts and other sections on New Providence. Elevations are from 1:2,500 scale topographic maps with 2-ft contours, corrected from datum (that was set at 1 m below present MSL), and for assumed subsidence of Bahama Banks of 3 m/125,000 yr (Lynts, 1970). Stippled lines are trends of beach ridges or tidal/beach bars.

TABLE 2. COMPARISON OF ABOUT 125,000-YR SEA-LEVEL ELEVATIONS (IN METRES) FOR NEW PROVIDENCE AND OTHER LOCATIONS

Location	Evidence	Elevation above MSL
New Providence	Keystone vugs	Up to 10.0*
Northern Bahamas (1)	Bioerosional notch	8.3–8.9*
Bermuda (2)	Wave-cut notch	4–6†
	aragonite on speleothems	
	keystone vugs	
South Florida (3)	Tops of oolite bars	9.2§
Barbados (4)	$\delta^{18}O$ versus sea-level calibration	
	on 1) coral	5**
	2) mollusk	10**
Yucatan (5)	Elevation of littoral deposits	5–6††
New Guinea (6)	Coral terraces and $\delta^{18}O$ versus sea-level calibration	8**
V28-238 (7)	Calculated assuming -0.1% change in $\delta^{18}O$ per 10-m rise in sea level	11

(1) Neumann and Moore (1975).
(2) Harmon and others (1978, 1981, and in press); P. Garrett and H. L. Vacher (unpub. data).
(3) Perkins (1977).
(4) Fairbanks and Matthews (1978).
(5) Szabo and others (1978).
(6) Bloom and others (1974), Chappell (1974), Aharon and others (1980).
(7) Shackleton and Opdyke (1976).

*Corrected for subsidence of 3 m/125,000 yr (Lynts, 1970).
†Presumed stable (Harmon and others, 1981, and in press).
§Corrected for subsidence of 1.2 m/125,000 yr (Lynts, 1970).
**Corrected for local uplift.
††Uncorrected for subsidence.

dence, phase III deposits are prograding beaches (as at Cable Beach) or beach ridges banked against phase II ridges (as at Old Fort Beach). Lyford Cay is a classic tombolo catenary on Simms Cay. Some phase III eolian ridges are as much as 6 m high.

The south shore has smaller beach ridges, rarely more than 2 m high and 50 m wide. They differ from the phase II tidal/beach bars in accreting against an earlier shore, rather than building up from marine-flats facies. Also, they are composed of skeletal (primarily molluscan) rather than the oolitic and pelletal sand of phase II bars.

Close to the south shore and in the interior of the island lie extensive and very shallow lakes. All lakes flood original shallow depressions in the Pleistocene surface, and all are floored with soft-pelleted calcite mud. The mud occupies an area larger than that of the present lakes.

Discussion of Phase III

We have one radiocarbon date on the *Cerion glans* from the eolian ridge at Delaporte Bay (Fig. 7). It is 3680 ± 550 C-14 yr B.P. (J. J. Stipp, 1981, personal commun.). Phase III thus is Holocene.

SUMMARY AND DISCUSSION

Facies

Figure 13 is a summary cross section of the known geology of New Providence. Note especially: (1) the thinness of the marine-flats facies sheet(s) and that the elevated phase II marine flats and its facies variants (tidal/beach bars and protected lagoons) make up the major portion of the present island; and (2) that eolianites form the prominent hills and ridges but are aerially small compared to marine flats.

This is quite a different situation from that of Bermuda, where eolianites form the bulk of the island's deposits, and marine deposits are the exception rather than the rule (Land and others, 1967).

Exploration of the subsurface, for example, by a borehole to a depth of 395 ft near the south shore of New Providence (Field and Hess, 1933) reveals that the oolitic limestone occurs only near the surface. Beneath are alternating beds of slightly cemented skeletal sand and cavernous limestone, dolomite appearing first at 160 ft. Further details of subsurface exploration through the Pliocene/Pleistocene of the northern Bahamas can be found in Beach and Ginsburg (1980).

Correlatives

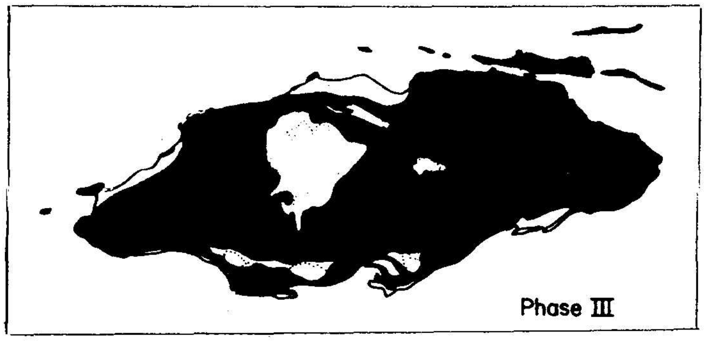
With the geologic history of New Providence so unfortunately devoid of radiometric dates, it is especially important to compare what data we have with better-dated Pleistocene sequences elsewhere.

Bermuda has the best-documented record for stable platforms (Land and others, 1967; Harmon and others, 1978, 1981, and in press) and there are similarities between its record and that detailed here for New Providence. The most striking similarity is the widespread Devonshire high sea level of Bermuda dated at about 125,000 yr (with a range of coral dates from 134,000 ± 8,000 to 118,000 ± 11,000 yr) (Harmon and others, 1981 and in press). This we correlate with our phase II high sea level for which we have only one date, 146,000 ± 9,000 yr (Neumann and Moore, 1975).

The correlation of a 146,000 ± 9,000 yr date with a high sea level at about 125,000 yr may seem farfetched. However, Neumann and Moore (1975) pointed out that their series of 16 dates showed no clustering within the spread of 94,000 ± 8,000 to 146,000 ± 9,000 yr, except around the mean value (approximately 125,000 yr). This suggests either that there may have been a broad sea-level maximum over the period or that errors in the coral dates may have occurred through the inclusion of as much as 5% calcitic impurities in the dated samples (Neumann and Moore, 1975).

The highest elevation of the phase II sea level on New Providence is considerably higher than that recorded for the Devonshire of Bermuda. It is not out of range, however, with elevations of the same sea level recorded in other areas of the

Figure 12. Paleogeography during phase III (Holocene) deposition. Legend same as for Figure 5. Notice that inland lake deposits are more extensive than present-day lakes.



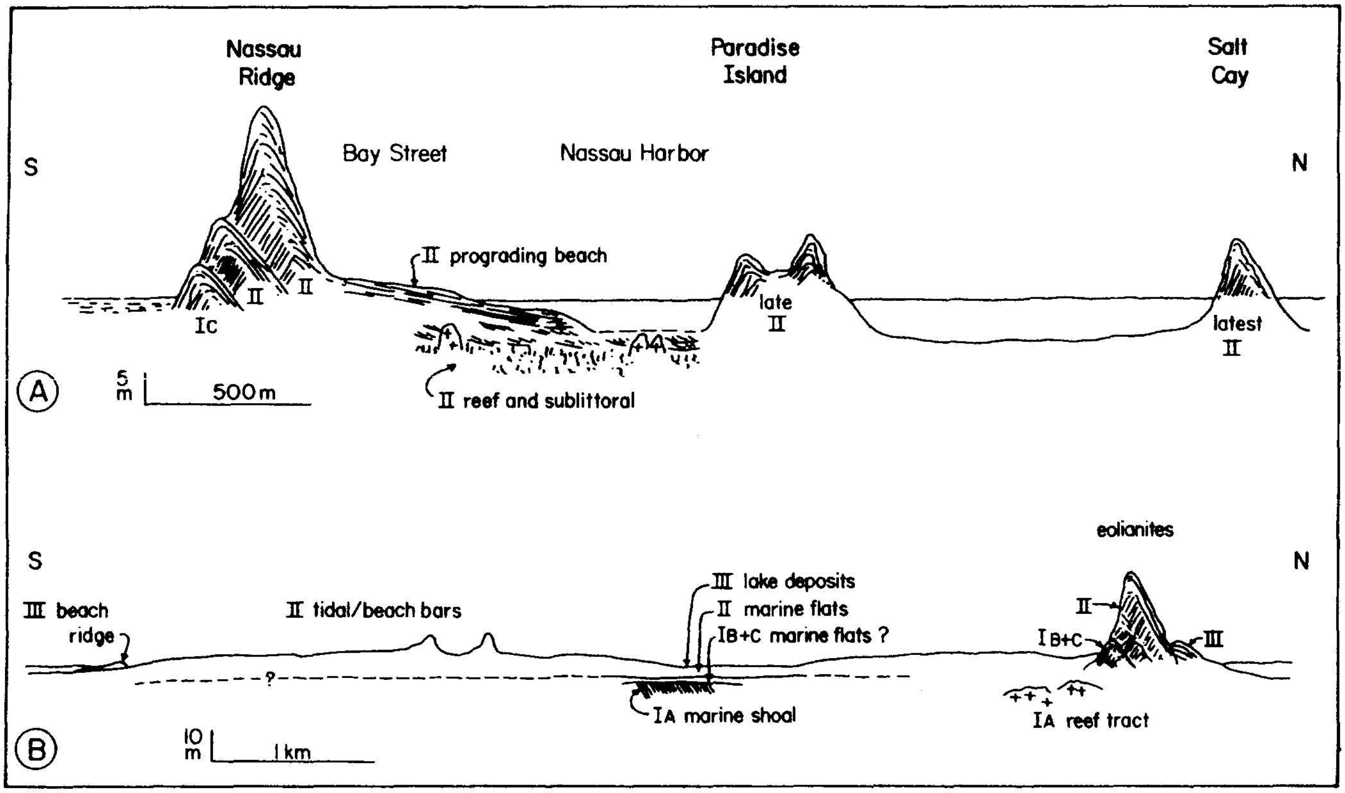


Figure 13. Summary cross sections of New Providence geology. A. South-north through Nassau showing the separation of the protected lagoon facies to the south of the Nassau eolian ridge and prograding beach facies (compare Fig. 9A) to the north. This prograding beach facies overlies reef tract deposits. B. South-north through Lake Killarney showing thin marine-flats facies sheets overlying the presumed lateral transition from marine shoal to reef tract of phase 1A.

world, using different criteria of sea-level estimation (Table 2).

In Bermuda, Harmon and others (1981, and in press) recorded pre-Devonshire eolian deposition, and it is pertinent to ask whether such a depositional event is recorded on New Providence. We believe that the unit i eolianite of locality 6 (Fig. 6) records such an event. The eolianite was in place and covered with a significant discontinuity surface before the deposition of unit ii, part of which records a sea level of +9.7 m. In addition, the Thompson Boulevard eolianite of locality 8 preceded deposition of the overlying marine shoal, which shows evidence of deposition at a sea level of between +7 and +8.7 m (Fig. 11).

Post-Devonshire eolian deposition is recorded in Bermuda from several sets of eolianites separated from each other by discontinuity surfaces. Harmon and others (1981, and in press) found that amino-acid racemization dates from these eolianites cluster into two groups at 105,000 and 87,000 yr, and that speleothem dates place contemporary sea levels at below −15 m. In addition, P. Garrett and H. L. Vacher (unpub. data) supplied evidence that eolian deposition was coincident with the fall of the 125,000 yr Devonshire sea level. On New Providence, there are many eolian ridges that could correlate with these events, for example, the many ridges between the north shore of New Providence, Athol Island, and Salt Cay/Rose Island. However, there is no proof of this correlation as yet.

If we accept that our phase II sedimentation is time equivalent to the Paget Formation of Bermuda (Vacher, 1973) (pre-Devonshire, Devonshire, and post-Devonshire of Harmon and others, in press), then other correlations hold, too, for example, to stage 5 of the marine ^{18}O record (Shackleton and Opdyke, 1976) and to unit Q5 in south Florida (Perkins, 1977).

Turning now to possible correlatives of our phase I, we note that the next oldest formation in the Bermuda section is the Belmont, dated by Harmon and others (in press) at about 230,000 to 200,000 yr. The Belmont of Bermuda consists of eolianites deposited both before and after a high sea-level stand at +2 m. A simple correlation might be that our phase IA represents the mid-Belmont high sea stand (the top of the marine foresets of locality 2 lies at −2 m after correction for subsidence, a point not inconsistent with a sea level of +2 m). The eolianites of phases IB and IC might then represent two episodes of post-Belmont deposition. Again, this is speculation: what is needed is a set of dates for the early phases of New Providence sedimentation.

Bahamian Islands

The exposed deposits of New Providence consist essentially of three facies: (1) extensive elevated marine deposits of a sea level higher than the present one, (2) eolianites, and (3) prograding beach ridges.

On a subsiding platform such as the Bahamas, if sea level were to remain constant, elevated marine deposits would be unknown.

As for eolianites, our evidence suggests that they did not occur in the area of New Providence before the late Pleistocene (200,000 yr). In addition, coastal carbonate eolianites to our knowledge have never been reported in pre-Pleistocene rocks anywhere. Are eolianites really such oddities, or is their nonoccurrence in the ancient record more a matter of nonpreservation or nonrecognition?

If eolianites are indeed unusual features, this leaves prograding beach ridges as the only likely facies of islands such as might dot the margins of ancient subsiding Bahama-type carbonate banks. Joulters Cay is one such island, developed entirely during the late Holocene (Harris, 1979). Is it an example of a "real" Bahamian island, and are most of the others, like New Providence, owing the bulk of their form and facies to the peculiarities of late Pleistocene higher-than-present sea levels or to sea-level oscillations in general?

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